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EVALUATION OF A DAMAGE ACCUMULATION MONITORING SYSTEM AS AN INDIVIDUAL AIRCRAFT TRACKING CONCEPT

Northrop Corporation, Aircraft Division
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This technical report has been reviewed and is approved for publication.

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The objective of this program was to study and evaluate the concept of using a damage accumulation monitoring system based on microprocessor technology for individual aircraft tracking, needed to satisfy the Force Management requirements of MIL-STD-1503A. The two major components of this study were: (1) the evaluation of selected output and input IAT parameters required to monitor the potential crack growth of each of two major classes of aircraft (Bomber/Transport and Fighter/Attack/Trainer aircraft), and (2) the definition of the microprocessor-based IAT system in terms of capabilities and requirements. A number of existing

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and planned IAT programs which were considered as typical for the two major classes of aircraft were studied to determine problem areas, to evolve advanced concepts, and to evaluate the output/input parametric requirements and the functional characteristics needed to satisfy IAT system goals. Several conceptual microprocessor based IAT systems and one existing microprocessor based IAT system capable of satisfying the requisite functional requirements were developed, studied, and described. In addition, the study was extended to examine the capability of microprocessor based IAT systems to satisfy, in part or wholly, the load and environment spectra survey (L/ESS) functions. Several system concepts were developed and described.

PREFACE

This report has been prepared by the Northrop Corporation, Aircraft Division, Hawthorne, California under Contract F33615-81-C-3204. This contract was administered by the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories. Lt. Rodney L. Wilkinson was the Air Force Program Monitor.

The program was conducted at Northrop with A. F. Liu as Program Manager. The report was prepared by C. Guadagnino, the Principal Investigator.

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GLOSSARY OF TERMINOLOGY

AFTO - Air Force Technical Order

ALC - Air Logistic Center

ASIMIS - Aircraft Structural Integrity Management Information System which has the task of coordinating and implementing a variety of IAT, L/ESS and FM data programs involving data processing analysis, reporting and distribution. The ASIMIS serves as a clearing house and is the responsibility of OC-ALC, Tinker AFB, Oklahoma.

ASIP - Aircraft Structural Integrity Program as defined in MIL-STD-1503A.

COBOL - A programming language designed for business data processing (Common Business-Oriented Language).

Control Point - A small region on the aircraft's primary structure which has been determined to be one of the more critical fatigue locations.

DADTA - Durability and Damage Tolerance Analysis

Damage Index - Is a measure of how much life has been consumed in terms of crack growth. It is the ratio of the used-up damage tolerance (crack growth) life to the predicted damage tolerance life at failure. This index is the abscissa of the normalized crack growth curve and is equal to one at failure.

Damage Index Limit - The fixed damage index value at an operation limit (usually critical crack length or failure) for any structural control point. For the generalized control point, normally the most critical, the damage index limit is equal to 1.0 if a scatter factor is not used since it represents 100 percent of the crack growth life. Secondary control points on the airframe would usually have longer crack growth lives, and therefore, their damage index limits would be greater than 1.0. Refer to the F-4 IAT program.

DI - Damage Index

D/DT - Durability/Damage Tolerance

DTA - Damage Tolerance Analysis

Flight (Load) Condition - A set of free body (rigid or flexible) aerodynamic positional and force parameters which define the equations of equilibrium for the aircraft at typical and critical points in its performance envelope. These parameters are used to define the external air loads for the particular static flight condition. Examples of commonly used flight load conditions would be high speed symmetrical pull-up, high speed symmetrical push-over, etc. The flight condition is sometimes referred to as the loading condition.

FM - Force Management

Fracture Limit - The time, in terms of flight hours, needed to grow to a crack from the initial crack size to the critical crack size.

FSM - Force Structural Maintenance

Generalized Control Point - For those IAT Programs which in effect track only one structural control point on the aircraft and predict the damage at the other control points by using a damage index ratio, the tracked control point is referred to as the generalized control point, the generalized location, or the monitored location.

Generalized Location - Generalized control point

IAT - Individual Aircraft Tracking

IAT System - The complete hardware and software system used to perform the IAT function. This includes the hardware located both onboard and offboard the aircraft, and the cumulative crack growth analysis, data processing programs, written procedures, etc. which make up the software part of the system.

Kft - Units of 1000 feet

L/E - Load Environment

L/ESS - Load/Environment Spectra Survey

Load Distribution - The distribution of the major external loads such as bending moment, torque, and shear concentrated along the elastic axis of the major structural components, that is, wing, fuselage and horizontal and vertical stabilizers. With the use of the finite element models and analysis,

the load distribution becomes a set of external vector loads applied at the nodes of the finite element model. By definition there is one load distribution for each flight condition.

Mission Profile - The mission profile describes the mission type in terms of mission segments and the major parameters needed to define and describe the mission segments. These mission segment descriptive parameters are the type of flying (ascent, cruise, decent, air-to-air combat, etc.), duration, altitude, airspeed, weights (gross, cargo, fuel, weapon) and any other operational performance parameters needed to define the structural load envelope or history of the aircraft.

Mission Segment - The smallest part of a mission type profile having a reasonably consistent set of operational performance parameters which minimizes the number of flight load or ground load conditions needed to describe the segment. Typical mission segments are cruise, ascent, and air-to-air combat.

Mission Type - An identifiable type of mission (usually originally described in the aircraft's design performance specification) which is defined by the mission profile.

Mission Usage - The experienced or anticipated usage that a single aircraft or a representative aircraft has flown or has been programmed to fly. The mission usage is usually made up of several different types of identifiable missions such as air-to-air combat, air to ground combat, long-range cargo mission, etc.

Monitored Location - See generalized control point

MSR - Mechanical Strain Recorder. A device used to mechanically record strain on a thin metal tape.

Operational Limit - Usually a time limit in terms of airframe flight hours for any type of aircraft structural integrity operational limitation such as; (1) the economical repair limit life, (2) the time to first inspection, (3) the safe life (durability) limit, (4) the fracture limit life and (5) the damage index limit.

RAM - Random Access Memory. The microprocessor's memory dedicated to storing data or user supplied programs.

ROM - Read Only Memory. The microprocessor's memory dedicated to storing operating programs and instructions.

SAG - Stop-and-Go practice landings.

Statistical Accelerometer - A sensing and recording instrument mounted on the aircraft to monitor and record the aircraft's experience in terms of linear normal acceleration factor. This instrument is usually limited to counting occurrences or load level crossings for four to ten preselected discrete values of the acceleration factor.

STEMS™ - Structural Tracking and Engine Monitoring System. A microprocessor based device developed by Northrop Corporation to monitor both airframe structural integrity and engine maintenance status.

TAG - Touch-and-Go practice landings

T.O.G.W. - Take-off Gross Weight

Tracking Point - Any point on the structure which is to have its crack growth history tracked by means of the IAT Program. The criteria for identification of a tracking point can be broad. A tracking point need not be fatigue critical.

Usage Parameter - Any measurement or set of measurements recorded during an aircraft's operational usage which describes the aircraft's operational usage, aerodynamic performance, or structural performance. There are several broad categories of usage parameters. Primary usage parameters are physically sensed and measured in real time as the aircraft operates. Secondary usage parameters are derived from the measured primary parameters by logical or arithmetical analysis.

The most common primary usage parameters are normally referred to as aircraft response parameters which are the standard aerodynamic and inertial parameters used to describe the flight of the aircraft. Other common primary

usage parameters are configuration parameters which describe the configuration of the aircraft and its components. A third category of parameters are (in this report) called flight parameters. Flight parameters can be considered as subsets of one of the above two categories but are sometimes considered separately because these parameters are not normally sensed by instrumentation and must be derived or calculated from manually input data.

In terms of operational usage, there are two categories of secondary usage parameters. These parameters are single parameters derived from a set of response, configuration and flight parameters occurring over a period of time and are called activity and event parameters. Typically, activity parameters are: a specific mission type, a specific mission segment type, or a specific load condition. Event parameters are parameter sets which define the occurrence of a discrete event such as a landing, an external store ejection, or a cargo drop. Both activity and event parameters are attempts to grossly simplify the analytic manipulation of more detailed phenomena.

VGH Recorder - A sensing and recording instrument mounted on the aircraft to monitor and record the aircraft's airspeed (V), linear normal acceleration factor (G), and altitude (H). This instrument usually produces time histories of the three parameters.

μP - Microprocessor.

LIST OF SYMBOLS

a_f	The limiting damage usually in terms of the crack length at failure. It is also equivalent to the critical crack growth (a_c).
D_C	The current date
D_P	The projected calender date usually in months or years at which time the critical crack length will be reached.
L	The full fatigue life of the aircraft or component (either based on test or analysis) in terms of flying hours for a specified mission usage.
RL	Remaining life of any critical point in the aircraft.
S	Severity ratio relating the true individual aircraft's mission usage (flying hours) with the analytic mission usage time (t_{MU}) for the baseline mission usage.
t_{AC}	The time (flying hours) accumulated by the aircraft or component being tracked.
t^*_{MU}	Current accumulated aircraft/component time (usually in flying hours) of a particular mission usage (MU).
t_{RL}	Time in flying hours of remaining life
$\tilde{U}$	Actual monthly utilization rate in flying hours per month for a specified programmed mission mix usage.
U_P	Planned monthly utilization rate (flying hours per month).

SECTION I

INTRODUCTION

This report describes a study which qualitatively evaluated (1) the characteristics of several conceptualized structural damage accumulation monitoring systems based on microprocessor technology, and (2) the capability of these conceptualized systems to satisfy the Force Management (FM) individual aircraft tracking requirements.

The goals of Force Management and Individual Aircraft Tracking (IAT) require a knowledge of the aircraft's air and ground load history because it is this usage history which determines the accumulation of structural damage. It follows that it is necessary to monitor those mission parameters which best describe the aircraft's usage and to develop - by means of the analysis of the recorded parameters - one or more measurements of the service induced damage. In turn, the analytic determination of the aircraft's structural damage status will be used to determine what force management actions are necessary. Therefore, IAT programs, regardless of how they were implemented in terms of hardware systems and manpower, have two chief functions, mission usage data acquisition and mission usage data analysis. Both of these functions have posed and continue to pose a number of operational, logistical, and analytical problems. The advent of microprocessor technology and its application to IAT and FM now offers the opportunity to resolve a number of these problems and to extend the effectiveness of IAT programs in ways not previously practical.

This study was organized around several different aspects of IAT methods and characteristics. First there is a distinction made between large class (bomber and transport) aircraft and small class (fighter, attack and trainer) aircraft. This distinction is arbitrary, but is based on the way IAT methodology has been developed over the last decade for those two classes of aircraft. The second aspect of this study is the differentiation and emphasis on IAT input parameters as separable from IAT output parameters. Briefly, input parameters

are defined as those aircraft usage parameters which are necessary input to the IAT fracture mechanics analysis, while output parameters are the damage metrics and correlated data resulting from the analysis. IAT output parameters become in turn inputs to the force management program. This emphasis on the difference between input and output parameters is carried through most of the discussions in later sections of the report.

As background to the subject, the goals of aircraft load monitoring are briefly discussed in Section II. Crack growth analysis methods and usage parameters are discussed in Section III in terms of their impact on IAT. Section IV is a brief discussion of current IAT problems as determined by recent discussions with ALC personnel and literature research.

A major part of the work in Sections V and VI was the study of a number of existing and planned IAT programs. It was felt that the basic concepts and structure of these programs would influence how microprocessor technology would be used in new IAT systems. The programs studied and discussed are the C-5A, C-141A, C/KC-135, and CT-39 transport IAT programs and the F-4C/D/E fighter, A-10A, and A-7D attack aircraft IAT programs. Other aircraft programs were briefly studied but not reported on.

The studies of the above aircraft IAT programs focused on the following areas:

(1) The identity of and the method of utilizing the aircraft's usage IAT input parameters,

(2) The identity of and method of generating the IAT output parameters,

(3) The cumulative crack growth analytic methodologies in use, and

(4) The equipment used for and methods of monitoring, recording, processing, and transmitting the IAT data.

With this data background, the study then proceeded to the evaluation of advanced microprocessor based IAT system concepts.

In Section VII, these concepts are described in greater detail in terms of system functional and design characteristics for a number of conceptual systems and one existing system. The definition of IAT system hardware/software capabilities and requirements are then more explicitly described in Section VIII.

Load/Environment Spectra Survey (L/ESS) systems were included as a secondary effort in Section IX in order to evaluate the impact of the microprocessor on the design of future L/ESS systems and to evaluate the feasibility of a microprocessor-based IAT system to perform part of the L/ESS function.

As a result of the description, study, and evaluation of a number of system concepts, several conclusions relative to the use of the microprocessor in IAT systems and recommendations for additional investigations - including design, prototyping, and testing of advanced microprocessor based systems - are presented in Sections X and XI.

In this study, all of the IAT and L/ESS concepts were approached from the point of view that they would be implemented on a dedicated microprocessor hardware system. However, this is just one of several different implementation approaches. It is feasible to implement the IAT and/or the L/ESS program by time-sharing the facilities of the onboard air data computer just as it is feasible to use a dedicated IAT microprocessor system or a dedicated IAT and engine maintenance microprocessor system. Each of these three implementation approaches has inherent technical and economic advantages and disadvantages which should be evaluated during development. This subject was not part of the study.

SECTION II

PURPOSE OF AIRCRAFT LOAD MEASUREMENT AND MONITORING

Aircraft load measurement and monitoring serves two broad purposes: design verification and force structural management. Both of these purposes are interrelated in the sense that there is considerable commonality of design and operational usage factors which impact both functions.

Current aircraft are designed and analyzed in a manner which pushes the designs to extremes of material and structural performance. It is not uncommon for airframes to operate at, and even above, the nominal design limit load or stress. While such high performance may be justified by modern analytical methods implemented by digital computers and more sophisticated methods of airframe structural testing and material testing, it points up the need to improve the tools used to develop the loads data which are, after all, the starting point in the design cycle.

1. Design Analysis Verification

Traditionally, the measurement and monitoring of aircraft loads was limited to the verification of design loading conditions, load analysis, and the verification and evaluation of the aircraft's static and dynamic aeroelastic response characteristics. These problems are of a static nature and in the case of dynamic aeroelastic problems, of a short term nature. However, in the past fifteen years, changes in the military specifications relative to structural durability and damage tolerance, and improvements in damage tolerance analysis and test methodology, have added another dimension to design load analysis verification. There is now a need to measure and monitor the aircraft's loading over the aircraft's entire service life. The current specifications [1,2,3] require the definition, use, and verification of a design service life load/environment (L/E) history or spectrum. Thus the dimension of time has been added to the load problem.

During the aircraft's design development, the specified service life load/environment history, by its nature and purpose, can only be a statistical or population mean requirement for the typical or nominal aircraft in the force. It is known from experience that a force of aircraft of the same model flown to the presumably same tactical mission will individually experience a variety of load/environment histories. These histories will, in terms of structural fatigue load severity, usually vary from the nominal design load/environment history. Thus the cumulative load/environment history experienced by the individual aircraft may be more severe or less severe than the design load/environment history. The questions to be answered are first: how does the force's composite load/environment history or spectra compare with the nominal design load/environment history and spectra, and second, what is the nature and magnitude of the force's deviation from the nominal design load/environment spectra?

The above problems are currently being handled, for the most part, by Load/Environment Spectra Survey (L/ESS) programs and to a smaller extent by Individual Aircraft Tracking (IAT) programs [2]. These two types of load/environment monitoring programs will successfully verify the design fatigue load spectra if the programs include an adequate population of the force and if the programs are implemented over an adequate percentage of the force's service life.

2. Force Management

The objective of Force Management (FM) is to ensure the durability and damage tolerance of an aircraft force throughout the useful life of each aircraft. To meet this objective, some form of Load/Environment (L/E) monitoring is useful, if not actually necessary. The Aircraft Structural Integrity Program (ASIP), as specified in MIL-STD-1530A, requires the development of both L/ESS and IAT programs to be used as tools in the FM program.

In terms of functions, FM can be divided into two catorgories: structural maintence, which is the chief function, and operational planning. For structural maintenance purposes, load/environment monitoring programs such as L/ESS and IAT can be used to update the Force Structural Maintenance (FSM) plan.

That is, the identification and scheduling of inspection, replacement, repair or modification actions. For operational planning purposes, load/environment monitoring programs can be used to modify the programmed mission mix for the whole force, or part of the force, and to preplan mission profiles on the basis of minimizing fatigue damage.

3. Development of Design Load Criteria for Future Aircraft

Another purpose of load/environment monitoring is the development of design load criteria (static strength and fatigue strength) for future aircraft. In the past, L/ESS types of data, collected usually from small groups of aircraft for finite time periods, have been used to develop the design load spectra criteria. However, because of the manner in which the load data are processed, and the small sample source and expense of data collection, the L/ESS data have not been used to show the scatter in the load spectra for a fleet's population of aircraft. The IAT program can be used to fill this gap if the cost of data collection can be reduced. A body of L/E spectra data obtained from a large population of aircraft will provide a composite history of the force's L/E exposure, and the deviation of the individual aircraft's L/E exposure from the mean. Such statistics will become more important in the future as design, analytical and testing methods become more sophisticated and less conservative.

4. Environmental Data

Except for high speed flight, little attention has been given to environmental data because of the characteristics of metallic airframes. With the advent of composite structures which are considerably more sensitive to environmental humidity and temperature, there appears to be a need for more precise statistical data on the aircraft's operational environment. While the difficulties of data acquisition and recording may limit the scope of any environment monitoring program, it seems necessary to collect this type of data in a L/ESS program and to perhaps sample the environment in an IAT program. For composite structures, the environmental history of the inactive aircraft sitting on the ground is just as important as the flight environment, and this would be a new and unusual aspect of such an environment spectrum survey.

The tracking of environmental data critical to composite structure will not be discussed since this study is limited to metallic aircraft.

5. <u>Individual Aircraft Tracking Program Related to the Aircraft Structural Integrity Program</u>

The Individual Aircraft Tracking program and the Load/Environment Spectra Survey program have been in extensive use for several decades to help assure the structural integrity of aircraft forces and are now integral parts of the design development cycle. Figure 1 illustrates the major tasks of the ASIP and the various related tasks for the design, development, and the implementation of an IAT program. The birth an IAT program starts with the Durability and Damage Tolerance Analysis (DADTA) task since many analytic elements of the DADTA are necessary for the planning and development of the IAT program. The DADTA and the structural fatigue/crack growth test programs will have a strong impact on the nature of the IAT program's crack growth analysis methodology and the selection of the aircraft's usage parameters to be monitored and used in the analytic part of the IAT program. These related tasks are shown in Parts 2 and 3 of Figure 1. One of the chief decisions is the selection and design of the analytic approach to be incorporated into the IAT program. Two general analytic approaches are in use, and regardless of whether the analytic approach type is parametric or non-parametric, the goals are the same - to provide a reliable means of analyzing the load/environment history of the individual aircraft. As will be made evident in Sections V and VI, a review of existing and planned IAT programs indicates that the type of aircraft and mission has a strong influence on the nature of the IAT program and its analytic methodology. All large class aircraft (bomber and transport) have used the parametric analysis approach while small class aircraft (fighter, attack, and trainer) have used both non-parametric and parametric approaches.

A key task (Part 3 of Figure 1) is the exercising and evaluation of the IAT analysis methodology. This is accomplished by the use of computer programs to simulate variations in the types of input parameters and variations in the details of the analysis [4,5] and will be discussed in Section III.

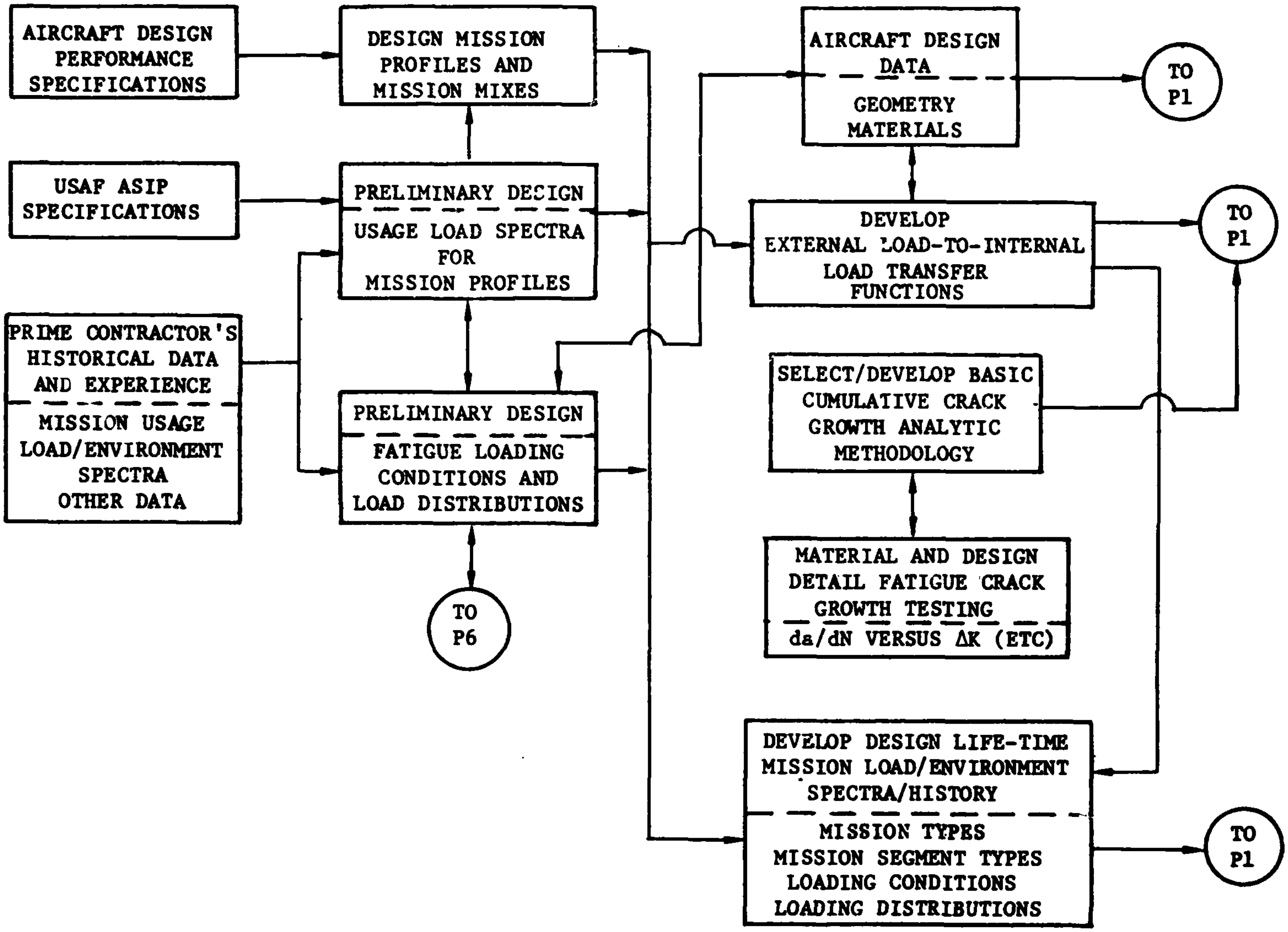


Figure 1. IAT Design, Development, and Implementation Tasks Integrated with ASIP Tasks (Part 1)

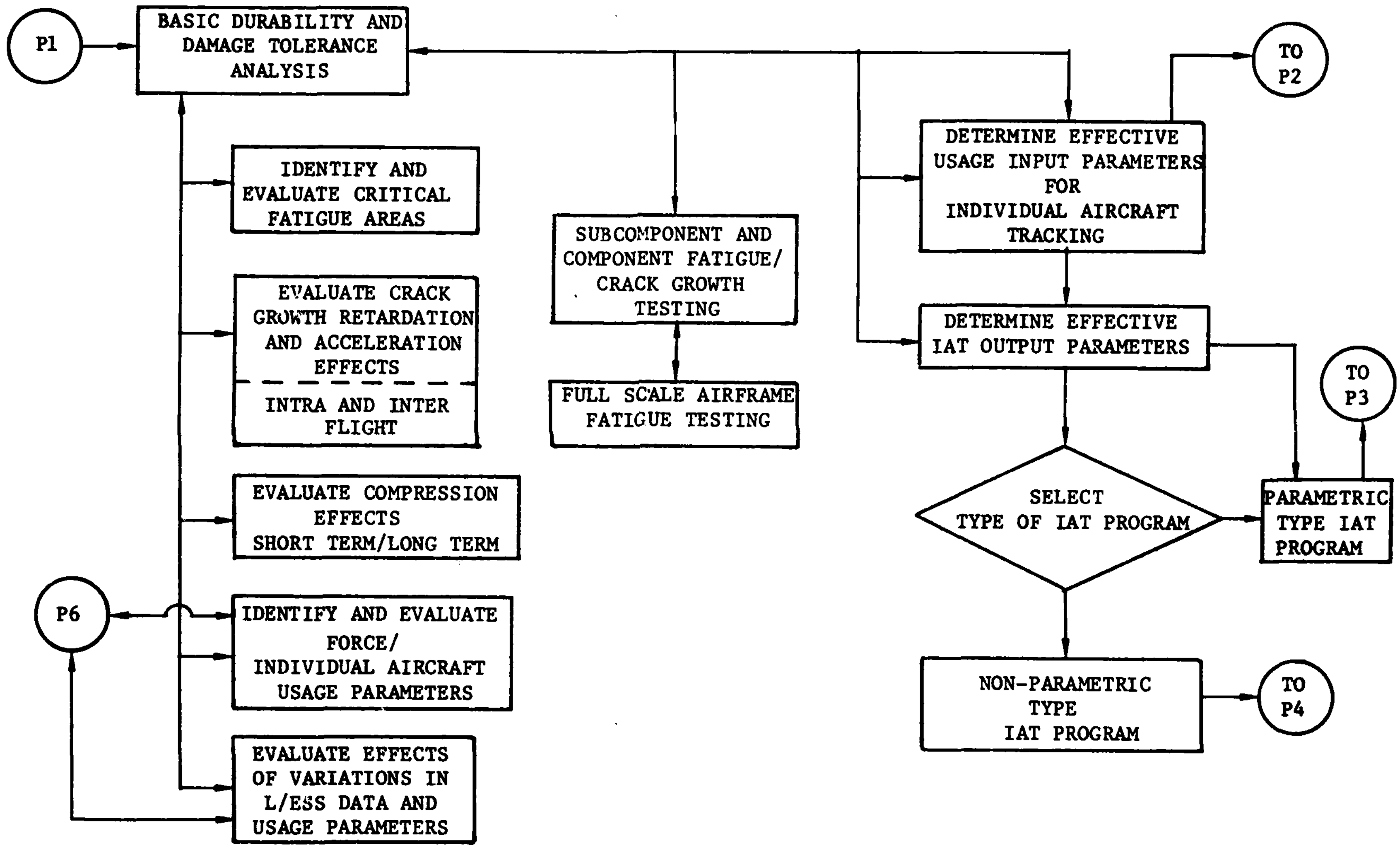


Figure 1. IAT Design, Development and Implementation Tasks Integrated with ASIP Tasks (Part 2)

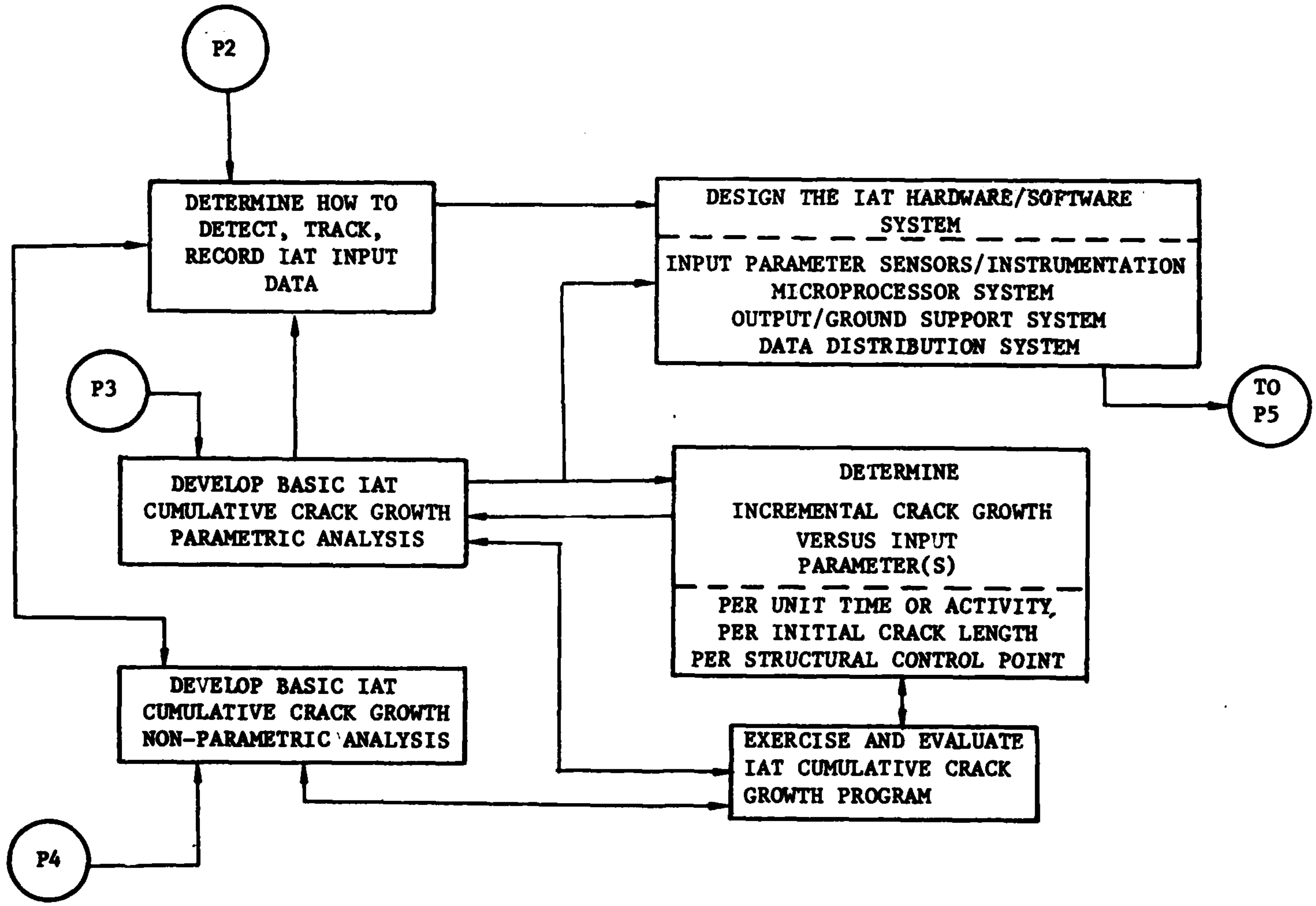


Figure 1. IAT Design, Development, and Implementation Tasks Integrated with ASIP Tasks (Part 3)

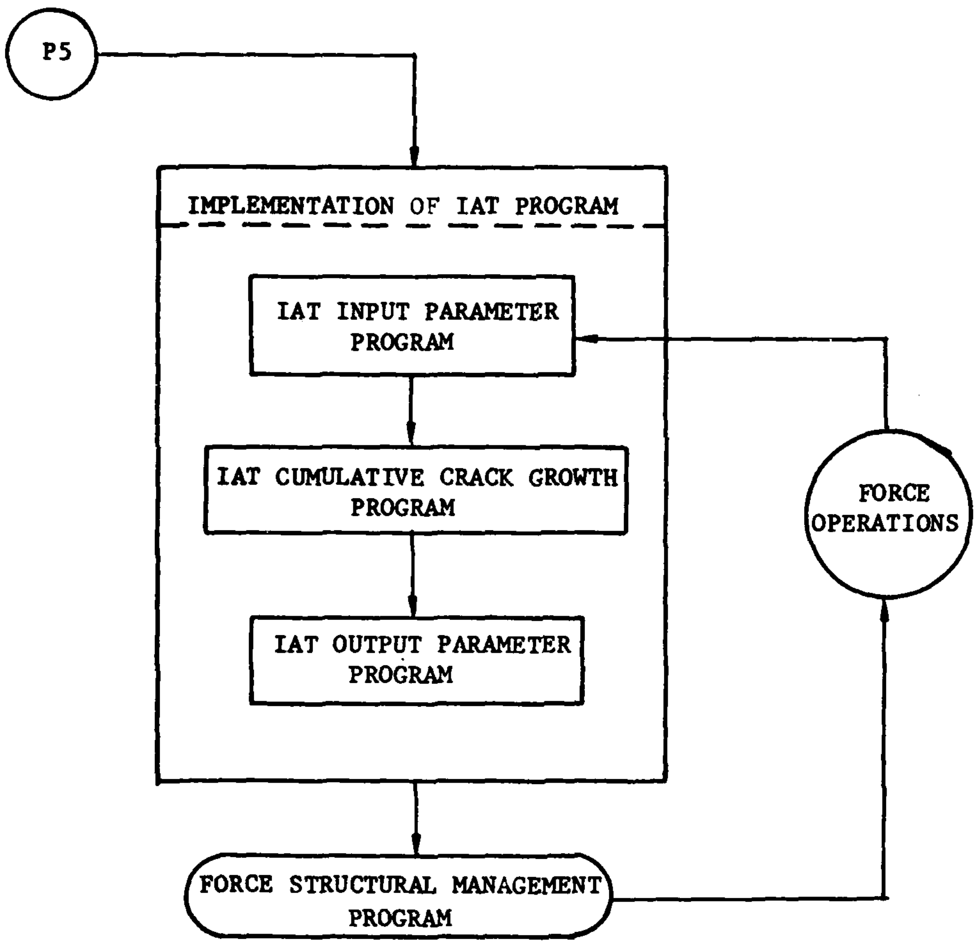


Figure 1. IAT Design, Development, and Implementation Tasks Integrated with ASIP Tasks (Part 4)

The primary goal of an IAT/FM program is to track the growth of any hypothesized pre-existing flaw or crack on the aircraft. To do this, any proposed IAT/FM system must perform three basic functions: (1) track the mission usage/load history, (2) apply a cumulative crack growth analytic methodology using the usage/load history and geometrical and material properties as inputs to track the fatigue crack growth, and (3) evaluate and utilize the IAT crack growth data using established Force Management procedures to accomplish the ultimate goals of MIL-STD-1503A. In the planning stages of the IAT program, the system designer has the option of implementing some of the above functions on the ground rather than on the aircraft. The first function - tracking the mission usage/load history - must be implemented while the aircraft is airborne. Figure 2 is a schematic showing the relationships between the basic functions of an IAT program, which are: (1) data acquisition, (2) data analysis, and (3) data evaluation and use.

A number of older aircraft systems have used and still use IAT analytic approaches based on a linear cumulative fatigue damage analysis (Miner/Palmgren Rule) or a residual strain/life analysis. Such analytic approaches do not meet current ASIP requirements. No attempt has been made in this study to evaluate such analytic approaches.

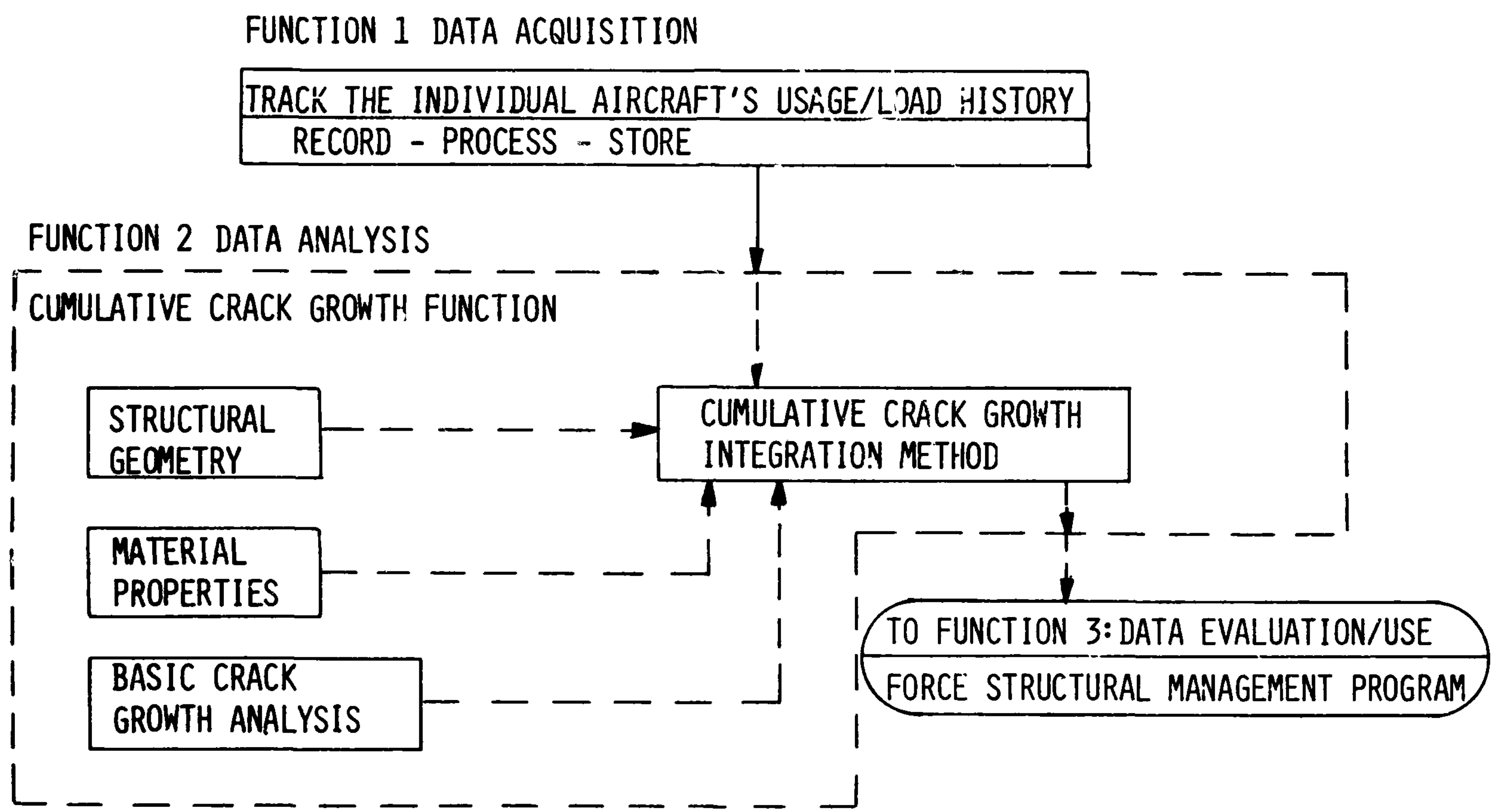


Figure 2. Basic Functions of the IAT System

SECTION III

DESCRIPTIONS OF METHODS USED FOR FATIGUE CRACK GROWTH TRACKING

In this section, several basic aspects of the IAT fracture mechanics approach are discussed in view of the nature and requirements of the IAT program. These aspects of the analytic problem include the parametric and non-parametric analytic approaches as well as the significance and impact of the Durability and Damage Tolerance Analysis.

1. Relationship Between Aircraft Usage and Analytic Tracking Methods

To fulfill the aims of the ASIP, the goal of any type of IAT system should be to determine and track the crack growth which is assumed to occur at each critical structural location (control point) due to the operational loads. In terms of a conventional damage tolerance analysis, the prediction of crack growth requires (other than material and geometrical properties) only two usage parameters: (1) the stress intensity factor, which is a function of stress, and (2) time - that is, the stress-time history (Figure 3). For this discussion, the exact nature of the crack growth analysis model is not relevent because it can be assumed that a reliable model will be selected and used. The central task can then be restated in terms of designing an IAT system to track crack growth damage as a function of stress which, in turn, is a function of some measure(s) or parameter(s) of aircraft usage. The various options in the planning of the IAT system are then related to the choice of usage parameters to be measured and the analytic method used to predict crack growth.

In regards to the latter choice, a review of various approaches used to date and discussed in this report indicates that all of the approaches use one of two analytic methods - parametric and non-parametric. These approaches are summarized in Part 2 of Figure 3 without regards to what part of the effort would be performed onboard the aircraft by the microprocessor (μP) or what part would be performed on the ground by large computers. Parametric IAT methods

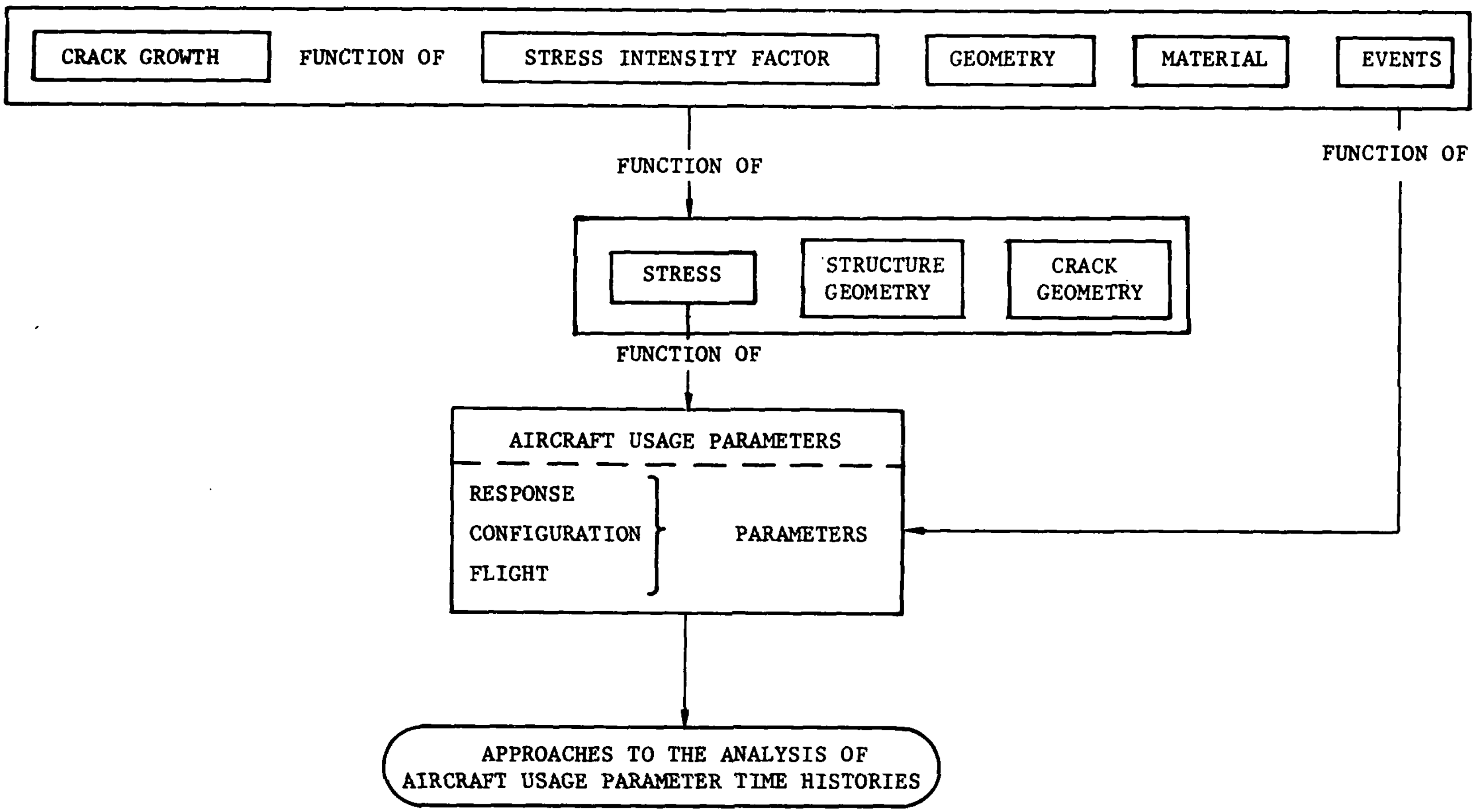


Figure 3. Outline of Several IAT Analytic Concepts (Part 1)

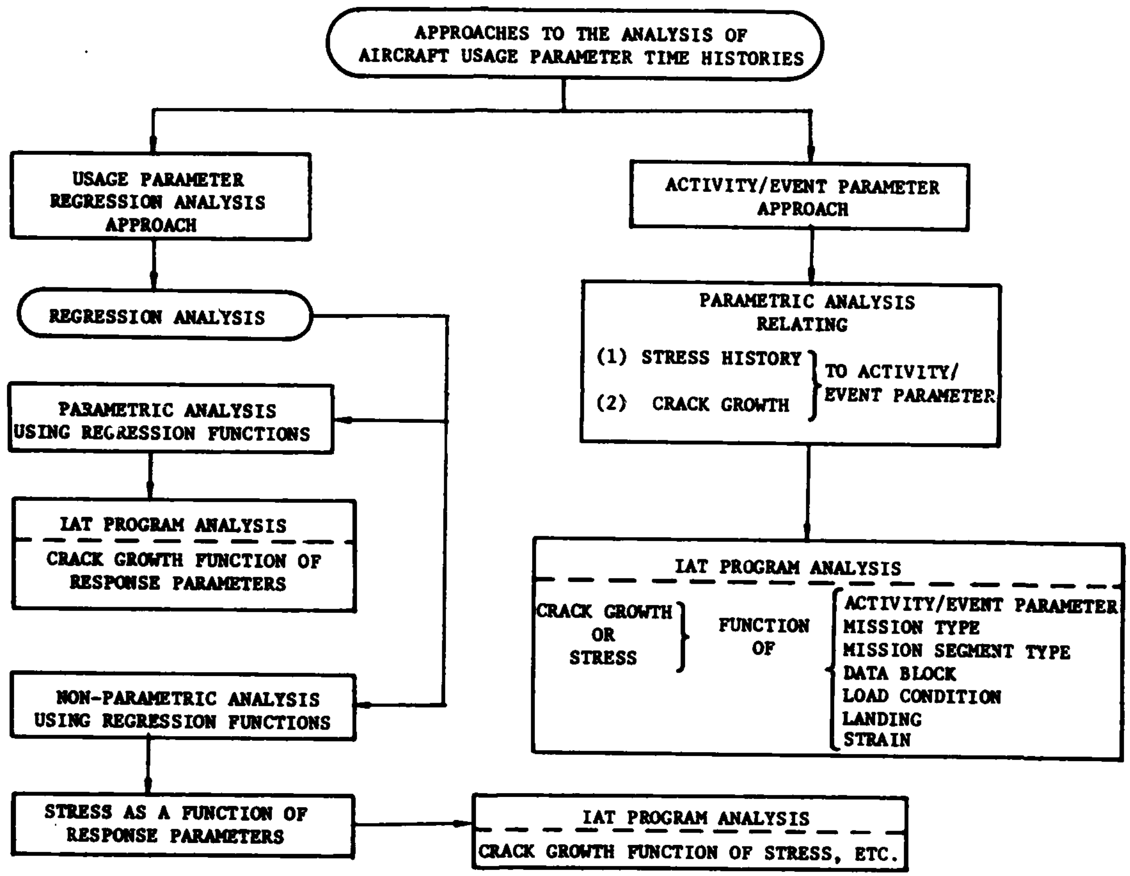


Figure 3. Outline of Several IAT Analytic Concepts (Part 2)

are defined as analytic models which use precalculated implicit relationships between crack growth and aircraft usage based on a family of analyses which relate incremental crack growth versus one or more usage parameters. That is, the usage parameter(s) defines the stress history which in turn defines the incremental crack growth history. For example, a group of specific mission types defines a group of typical stress histories, each of which then defines a series of crack growth histories based on a family of initial crack sizes. The C-5A IAT program is an example of this approach and it is discussed in Section VI.

Non-parametric IAT methods are defined as crack growth analysis models which directly calculate the crack growth history, load cycle by load cycle, using direct or indirect measure(s) of the stress history. An example of a non-parametric approach using a direct usage measurement (or parameter) would be the use of an electric resistance strain gage mounted on the structure to generate the stress history which is then used by the μP's program to calculate the crack growth. An example of using an indirect approach is the A-10A attack aircraft IAT program where the stress is not measured but is calculated (by the μP) as a function of several measured primary usage parameters such as normal load factor, aircraft weight, and airspeed. The μP then calculates the crack growth as a function of the previously determined stress history.

The question of what usage or input parameters are to be used in the IAT program is related to the method used to develop the external load-to-stress transfer functions. The more mathematically oriented approaches use some type of regression analysis of L/ESS-derived primary usage parameter data to generate a mathematical relationship between crack growth or stress and the key usage parameters. An example of this approach is the A-7D IAT program [5,6] which is briefly described in Section V. In this example, the derived regression functions (relating stress to the usage parameters) are used in a parametric analysis to generate a relationship which indirectly relates normalized crack growth (in terms of a damage index) to the selected primary usage parameters.

In a slightly different approach, the A-10A IAT prototype program described in Section V uses the regression analysis to relate structural control point stresses to selected primary usage parameters. In turn, these stress regression functions are used in a non-parametric cumulative crack growth analysis for a load cycle-by-load cycle calculation.

2. Significance of the DADTA to IAT Analysis

The Durability and Damage Tolerance Analysis (DADTA) of an aircraft type is the foundation and prerequisite for the IAT analysis methodology regardless of the nature of the IAT Program. The DADTA design load data are used to define:

1) The planned mission profiles and mission mixes
2) The fatigue loading conditions
3) The external loads spectra and history
4) The external loads-to-internal loads relationship for all loading conditions
5) The identification of all critical structural members and locations
6) The internal load spectra and history for all critical locations
7) The material properties
8) The basic cumulative crack growth analysis method
9) The identification of those usage and load spectra characteristics important to IAT and
10) The identification of those crack growth analysis characteristics important to IAT.

In a general sense, the IAT analysis is developed from the basic elements of the DADTA and is a means of verifying or correcting the DADTA crack growth predictions and inspection requirements.

The reliability of the IAT program depends on all of the ten data items listed above and particularly on the last two - the identification and definition of those usage parameter characteristics or factors which influence the effectiveness of the parametric crack growth analysis or the basic cumulative crack growth methodology.

Figure 4 shows the parallel development of both the parametric and non-parametric types of IAT analysis. In both cases, deviations in the expected values of either the force mission usage parameters, the crack growth analysis parameters, or the IAT analysis parameters will negatively affect the program's reliability. However, the parametric type of IAT program is more sensitive to the variations in various parameters and factors than is the direct type of IAT analysis.

3. Selection of Alternate Analytic Approaches

The selection of the IAT analytic approach is determined by three factors:

(1) The complexity of the external-to-internal load analysis

(2) The number of usage parameters which can be economically and technically included in the IAT input parameter data set

(3) The required analytic accuracy considering the sensitivity of the crack growth predictions to the number, variety and precision of the key input usage parameters.

The decision to use either a parametric or a non-parametric analytic method is a matter of subjective judgement for some aircraft since both methods could be equally effective. For other aircraft types, the parametric approach has a number of practical advantages. For example, large aircraft such as transports experience a loading history which is reasonably predictable in terms of the statistical occurrences of loads. It is obviously very difficult to develop a deterministic definition of the external-to-internal load relationship and in many cases it is not necessary. One of the major components of the transport loading history is the incremental load history due to air turbulence which can only be predicted statistically. In addition, it has been shown [7] that the ordering of the load cycles within a mission segment or a mission has a negligible effect on the predicted crack growth. Therefore the random application of the loads in the analysis is an acceptable practice and justifies a parametric approach.

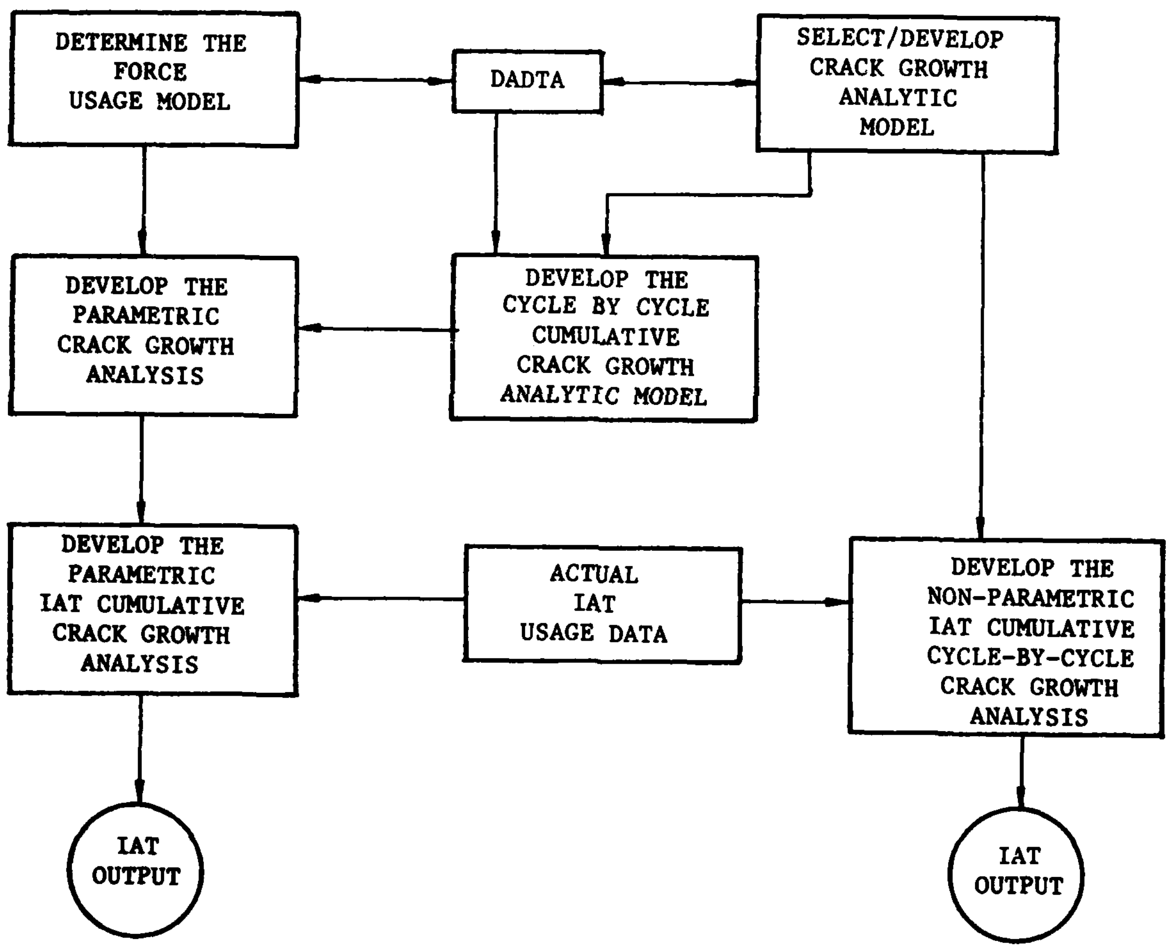


Figure 4. Parallel Development of Parametric and Non-Parametric Types of IAT Analyses

4. Parametric Types of IAT Programs

Effect of Variations in Usage and Analytic Factors and Characteristics

The basic approach for parametric types of IAT analysis programs is to calculate the crack growth damage for a range of typical planned aircraft mission service histories. The major difficulty is that many aircraft usage variations and crack growth analysis variations must be accounted for in advance and then built into the parametric analysis. Therefore, it is necessary to predetermine the effects of both usage and analytic methodology variations and their importance before freezing the design of the IAT parametric analysis.

There is considerable overlap between the usage variations and analytic methodology variation problems because the variations are often due to the same causative factors. In this section, the parameter variations will be discussed only from the aspect of parametric types of analytical methodology. The important factors will be identified and evaluated. Most of the data comes from References [7] and [8] and applies to both small and large aircraft.

The approach used in both references ("Effect of Fighter Attack Spectrum on Crack Growth" and "Effect of Transport/Bomber Loads Spectrum on Crack Growth") was to generate a baseline usage spectrum and a set of variational spectra where one or more factors or characteristics such as those listed in Table 1 were changed. The predicted crack growth life based on the variational spectra were then compared to the predicted life based on the baseline spectra. Simple structural specimens were fatigue tested using the baseline spectrum and many of the variational spectra to refine and verify the analytic predictions.

The results from both references are summerized in Table 1. Overall, the two references reached similar conclusions as to the qualitative trends though there were differences of degree when the specific factors were examined. As a result of referenced studies [7,8] the overall conclusions to be drawn are:

1) The reliability of the IAT analysis depends on the accurate description of the force's usage history

2) The more important usage parameters and factors impacting the reliability of the results, regardless of the type of analysis, are those which determine the:

   a. Stress cycle amplitudes
   b. Stress cycle sequencing
   c. Number of stress cycles and
   d. Stress cycle peak to valley ratios

3) The more important factors or usage parameters from the point of view of how these factors are handled within the crack growth model and the parametric model are:

   a. Low amplitude load cycle truncation
   b. Compression load cycles
   c. Distribution of high amplitude loads and
   d. Parameter interval size and distribution.

Many of the above conclusions have been verified in the course of the development of IAT programs for other aircraft, such as the C-5A.

Since a parametric analysis uses a predicted mission L/E history as the applied load history for the crack growth analysis, it can best be used for those aircraft which fly types of missions that can be predicted with a high degree of confidence. For aircraft models already in service the predicted mission L/E is usually based on actual past usage L/E data. In general, transports and bombers are in this category because of the repetitious nature of many of their missions. But in spite of this, 120 types of missions were required to account for 85 percent of the C-5A force-wide mission usage. The remaining 15 percent of the C-5A mission usage must be analyzed using a direct analytical method rather than the parametric method.

The F-4 fighter also uses a parametric crack growth analysis. In this case, because of the wider range of the expected load histories, the parametric analysis was performed for three degrees of load spectrum severity: severe, moderate, and mild. In all cases, the reliability of the parametric

TABLE 1. IMPACT OF VARIATIONS IN DEFINITION AND/OR APPLICATION OF USAGE PARAMETER FACTORS ON THE PARAMETRIC CRACK GROWTH RATES AND THE ANALYTIC METHODOLOGY

USAGE PARAMETER FACTORS THAT WERE VARIED TO PRODUCE VARIATIONAL LOAD SPECTRA	CHANGE IN PREDICTED LIFE
Definitions of Mission Mix	VS 1
Definitions and Inclusion of Low Altitude Penetration Segments	VS
Definitions of Mission Duration	2 NS to VS
Mission Sequence Definitions	NS to VS
Simplified Definitions of Segments	NS
Definitions of Exceedance Spectra	VS
Definitions of Design Stress Level	VS
Mission Segment Sequence Definitions	NS
Definition and Inclusion of Ground Loads	S 3
Combined Definitions of Design Stress Level and Low Amplitude Load Truncation	VS
Definition of Spectra Stress Ratio Content	VS
Method of Coupling Load Valleys to Peaks	NS
Low Amplitude Load Truncation	S
Inclusion of Compression-Compression Load Cycles	NS to S
Inclusion and Distribution of High Amplitude-Low Frequency Loads	VS
Clipping of High Amplitude-Low Frequency Loads	VS
Parameter Interval Size and Distribution	VS
Combined: Valley to Peak Coupling and Low Amplitude Load Truncation	S
Sustained Compression Loading	Unknown

Notes:
1. Indicates a Very Significant (VS) change in predicted life, that is, greater than 50 percent.
2. Indicates No Significant (NS) change in predicted life, that is, less than 10 percent.
3. Indicates a Significant (S) change in predicted life, that is, greater than 10 percent, but less than 50 percent.
4. Data Obtained from References 25 and 30.
5. Reference (30) defined a significant change as ranging from 20 to 100 percent of the baseline life.

analysis depends on the quality and quantity of the L/ESS data used to define the load or stress spectra for the full range of anticipated aircraft usage. For the F-4 aircraft, 3.5 million flight hours of statistical accelerometer data and 40,000 flight hours of VGH data had been acquired. This large mass of flight load data gives confidence in the reliability of the load spectra used in the parametric analysis. Nevertheless, the mission mix and load spectra for an aircraft model may change over a period of many years. For example, the number of 6g load factor exceedances per 1000 flight hours changed from about 100 in 1963 to 400 in 1971 (Reference 9, page 80). Variations in the load history such as this make IAT and L/ESS programs a necessity.

5. Non-Parametric IAT Programs

An analytic approach to tracking which calculates the cumulative crack growth from a tracked stress cycle history is referred to, in this report, as a non-parametric IAT program. The tracked stress history may be directly monitored and recorded by means of an electric resistance strain gage or mechanical strain recorder system or indirectly obtained by calculation, using the aircraft's usage input parameters as inputs to the stress calculation program.

A typical example of an indirect non-parametric approach is in the A-10A program described in Section V.

6. Explanation of IAT Parameter Terminology

During the course of this study, it became apparent that a number of terms used to discuss IAT parameters in the literature had overlapping or confusing meanings. It is helpful, for the visualization of the various IAT concepts discussed in this report, to explain the various categories and subcategories of IAT parameters.

There are two major groups of parameters: input (or usage) and output parameters. These will be defined in greater detail in the following paragraphs.

Input Parameter Catagories

Input parameters indicate how the aircraft is used and serve as inputs to the cumulative crack growth analysis program. Because of the way in which input parameters are obtained, processed, and utilized, it is useful to distinguish two catagories: first level and second level input parameters (See Figure 5). The first level parameters are those which are directly sensed via instrumentation or manually input for the flight. These directly sensed and recorded first level parameters fall into three catagories:

(1) The aerodynamic response parameters such as airspeed, altitude, load factors (mass linear acceleration), rotational velocities and accelerations, stress, sink speed, angle of attack, time, etc.

(2) The aircraft configuration parameters such as flap position, spoiler position, elevator deflection, landing gear position, external stores and weight distribution, sweep angle for variable geometry aircraft, etc. and

(3) The flight parameters such as gross take-off weight, fuel weight at various points in the mission, cargo weight, type of tactical activity undertaken, and in general any descriptive parameter which can not be economically sensed by instrumentation and must be manually recorded.

These first level input parameters are processed, either onboard the aircraft or at a ground facility, to generate the parameters required as input to the cumulative crack growth analysis. As will be apparent from the reviews of ongoing IAT programs (Sections V and VI) the nature of the parameters input to an IAT analysis vary widely and depend on the type of analysis. They are catagorized as secondary input parameters and there are three subcategories.

(1) The modified/filtered/correlated aerodynamic response parameters, such as a normal acceleration time history which has had the low amplitude-high frequency cycles filtered out

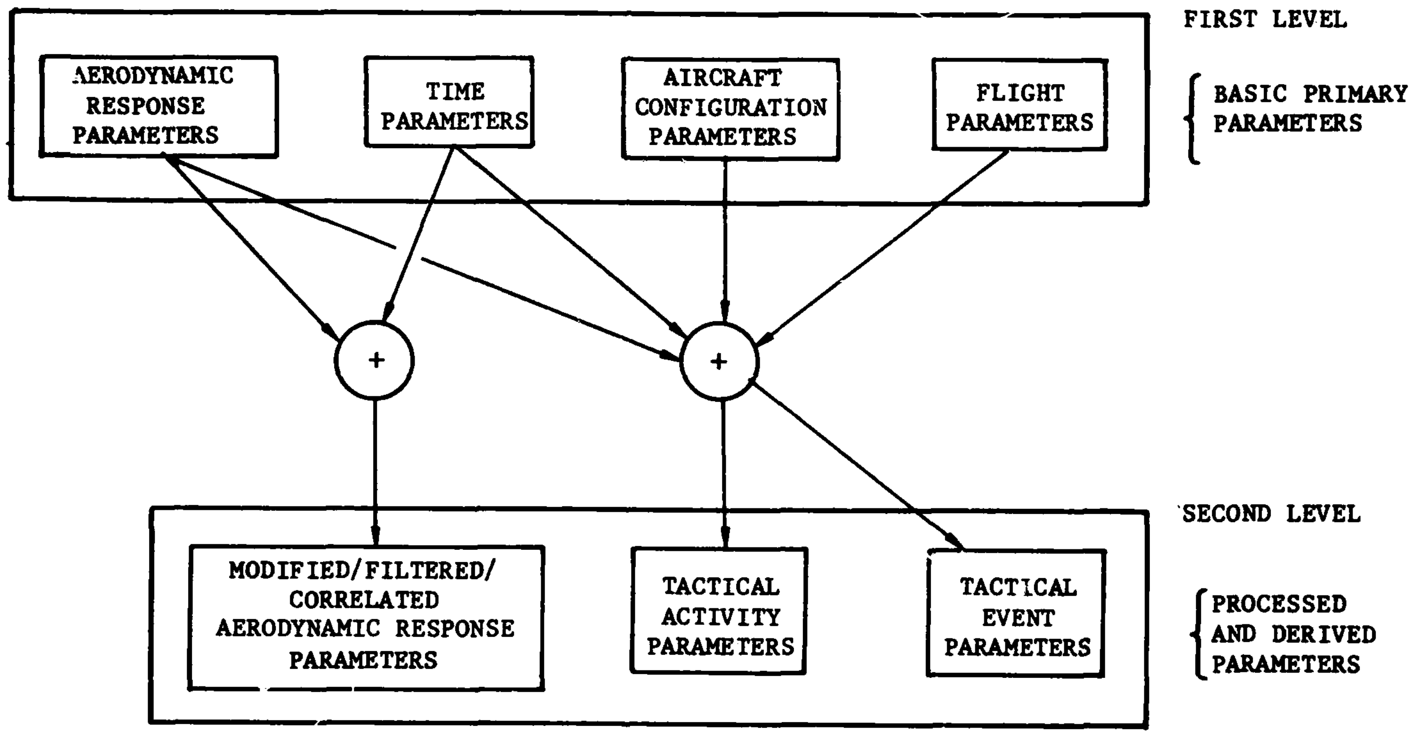


Figure 5. Classification of IAT Input Parameters

(2) The activity parameters such as the identity and occurrence of a specific predefined type of mission, or type of mission segment, and

(3) The event parameter such as the identity and occurrence of an event such as an external store drop event or a stop-and-go landing event.

The term used for the first subcategory has not changed. Response parameter refers to either the raw (first level) data or the processed form of the raw response data. Both the activity parameter and the event parameter are derived from a set of first level parameters in a manner which depends on the aircraft and its IAT program logic. This aspect will be discussed in later sections.

Output Parameter Category

The output of a IAT cumulative crack growth analysis will be some parameter which measures the incremental or cumulative crack growth damage. The exact nature of the damage parameter will depend on the individual IAT analysis. The most common output parameter is either crack length or a damage index number for the specified structural location being tracked. Refer to Sections V and VI for details.

In addition to the above, the IAT output parameter set will include identification (or documentation) parameters and perhaps additional damage rate parameters. See Section VII.

SECTION IV

REVIEW OF PROBLEMS WITH CURRENT IAT SYSTEMS

A part of the study effort was the task of considering the nature of the problems which the USAF is experiencing in the day-to-day operations of the IAT programs. Conferences with Air Logistic Center (ALC) personnel responsible for various IAT programs provided insights - summarized below - into the problems that the ALC's have experienced and the solutions favored by them. In addition, the literature was researched to add to this store of background data.

1. Discussions with Air Logistic Center Staffs

During the month of February 1981 the principal investigator travelled to each of the five regional Air Logistic Centers (ALC) for discussions with the cognizant personnel working on the various IAT and FM programs and related activities.

The following findings apply in general to all of the ALC aircraft system programs.

1. The IAT and FM programs have been shaped by five factors: (1) the preexisting logistics system into which the programs were fitted, (2) the time when the programs were initiated and developed and when the aircraft were designed, (3) the operational priority of the aircraft system, (4) the number and severity of fatigue problems experienced by or anticipated for the aircraft, and (5) the class of aircraft, i.e., bomber/transport or fighter/attack/trainer.

2. Force Management methods in use are generally similar for all classes of aircraft. One exception is the C-5A transport which, due to its many fatigue problems, requires a considerable amount of activity.

3. The IAT programs vary considerably in scope and approach. Both Miner's Rule linear cumulative damage analysis and fracture mechanics based crack growth analysis are in use. Most IAT programs may be classed as parametric programs as defined in Reference 4. The IAT usage parameter data acquisition methods vary greatly with Flight Logs, Statistical Accelerometers, VGH Records,

and Mechanical Strain Recorders being used as the primary source of data. However, the most prevalent usage parameter acquisition system is the Flight Log.

Almost all ALC personnel expressed a need to improve the IAT and L/ESS programs by reducing the amount of manual tasks required at all logistic levels.

2. IAT System Problems

In determining the input/output requirements, it is necessary to consider two interrelated but dissimilar problems: first the practical logistical problems faced by USAF in the day-to-day operations of IAT and Force Management programs and second, all aspects of the IAT analytic flaw growth methods which impact on program reliability and effectiveness.

In the past, the logistic problems and their solutions were necessarily influenced more by the state-of-the-art hardware capabilities (usage parameter recorders) and funding limitations than by analytic limitations. When the first generation of IAT and L/ESS programs were started in the 1960's, analysis capability was limited to Miner's Rule fatigue analysis. The changeover from fatigue analysis to fracture mechanics based crack growth analysis has made difficult data management problems even more difficult. Moreover, the same type of logistic management problems caused by the hardware/software restraints persist to this day. Even though crack growth methodology has matured considerably in the last ten years, neither industry nor the USAF can fully utilize this methodology because of restraints inherent in the hardware systems and their associated data management problems.

Crack growth damage accumulation analyses require, as input data, the far field stress history for the structural control point under consideration. Because of hardware limitations, the stress parameter cannot be easily or inexpensively recorded, and thus the state-of-the-art solution was to measure parameters such as normal acceleration load factors. When feasible, a number of other external load parameters were included to add to the accuracy of the stress calculations. While this is a good engineering solution which is used industry wide, it must be acknowledged that the load data management problem (collecting, storing, reducing, editing, and analyzing) is a considerable task.

To minimize the data management problem, the industry and the USAF have developed and put into operation IAT crack growth analysis methods which are designed to bypass or solve many of the data problems. The general approach has been to modify the IAT analytic methods so that the analysis would reliably function using input data based on a minimum of collected usage data. Usually this necessitated the development of an implied relationship between the stress history required by the analysis and an easily recorded set of usage parameters such as the identity of the type of mission flown and a few other key parameters. In other cases, an implicit relationship between the incremental crack growth and the simplified usage parameter set was developed, thus bypassing the need for an explicit stress history-to-usage parameter relationship. A considerable amount of engineering effort as evidenced by USAF technical reports [References 4, 7, 8, 10] and the literature [11] has gone into the development of analytical techniques which will produce the most analysis for the least cost and the simplest form of load input data.

It is believed that the microprocessor will solve many of the current IAT and L/ESS data acquisition and processing problems. However, the microprocessor, as powerful and as important as it can be to the IAT system, is still dependent on the usage parameter sensors and transducers. In the worse case situation where the IAT system has few usage sensors and relies on a parametric damage analysis approach, the microprocessor will still function as a powerful analytic tool which will optimize the inherent analytic possibilities by extending the scope and complexity of the parametric approach. The actual logistic and data management problems which can be eliminated by a microprocessor depend on what type of IAT program the microprocessor system is fitted into. To make full and effective use of the microprocessor, the fleet program and the microprocessor system should be tailored to complement each other. USAF logistic and funding limits will influence the decision as to how to use the microprocessor in IAT programs (for example transport programs) where the only technically and economically viable approach may be through the use of the parametric type of analysis.

3. Conclusions

The various IAT system problems described in the literature [4] still exist. Current IAT programs: (a) require too much manual effort at all echelons, especially at the lowest operationsl levels, (b) require too much calender time to produce analytic results that can be used by the force manager, and (c) exhibit low to moderate efficiency relative to input data acquisition and analytic reliability. Most of the IAT analytic programs and IAT data acquisition systems have understandably been designed to minimize system costs rather than to maximize system accuracy and reliability. One of the most significant aspects of this problem has been the hardware; that is, the relative lack of simple-to-use, inexpensive, reliable, automated data acquisition and data processing devices. However, through the use of microprocessor technology, many of the manpower, hardware and fiscal problems can be resolved.

SECTION V

CASE STUDIES OF FIGHTER/ATTACK/TRAINER CLASS IAT PROGRAMS

In this section, the ongoing IAT programs for the A-10A and A-7D attack aircraft and the F-4 fighter aircraft are reported. These aircraft were selected for study because their IAT programs are representative of small class aircraft. The new A-10A IAT program is discussed in greater detail because it is the first program to fully utilize the microprocessor (μP). The A-10A IAT system serves as both a conceptual model and a practical example of the potential of the μP based IAT system.

Other small class aircraft IAT systems such as the F-16, F-111, F-5 and F-15 were studied but are not discussed in this report because they are not adequately described in the literature [4].

1. Case Study: Fairchild A-10A Attack Aircraft

Background

In 1978 the Northrop Electronics Division was contracted to develop, construct, and install a prototype μP-based Engine Maintenance Monitoring System on the A-10A aircraft. This program was subsequently enlarged to include structural tracking, and the combined μP system is currently known as the Structural Tracking and Engine Monitoring Systems (STEMS)™. Currently, the Northrop Electronics Division is under contract to develop, design, construct, install, and implement an operational IAT system for twenty-eight (28) A-10A aircraft. The basic DADTA data required to develop the μP software were obtained from Fairchild [12,13]. Although the original program included a requirement for a fatigue analysis [14, 15], only the crack growh IAT program will be described here. The current STEMS™ system can be used to track four fuselage control points - one engine nacelle pylon control point, two empennage control points - and three wing control points.

The STEMS™ is a solid state electronic unit developed by Northrop, which contains a microprocessor, a memory unit, a power unit, a series of signal conditioning units, and an input/output system. Processed data are stored in memory until it is electronically output to a portable ground retrieval unit. A number of sensors and transducers are used to sense data signals (eight times a second) and to input the data signals to the signal conditioning units within the STEMS™ device. These signals are converted by the conditioning modules to data signals in engineering units and then stored temporarily in random access memory (RAM) until processed. A complete cumulative crack growth program, an operating system program, and a library of background data are stored in the μP system. These programs are loaded into the aircraft's STEMS™ unit by means of the portable ground data retrieval unit and can be modified if required. The portable ground data retrieval unit is also a μP controlled unit with solid state memory, and its functions are to: (1) retrieve the onboard μP stored data, (2) temporarily store the output data until transferral to the next or final user, (3) post-process the aircraft's data to give interim IAT data, engine maintenance data and equipment status data, and (4) load computer programs and IAT program data into the aircraft's μP system.

Three different μP based IAT programs of varying complexity were developed and evaluated for the A-10A aircraft. The evaluation (completed early in 1982) resulted in the selection of the Program 3/Multiple Control Point IAT System. The two rejected programs will be briefly described, and the selected program will be described in greater detail in the following section because of its importance.

Program 1/Parametric Method: This IAT program uses the μP as a statistical accelerometer to collect numbers of normal load factor (n_z) occurrences for eight load factor bands. The statical n_z data are retrieved from the aircraft using a ground data unit and transferred to a ground based computer center. Here the load factor data are analyzed using a parametric relationship developed in the DADTA, which can be briefly expressed as:

$$a_i = a_o + \sum \Delta a \qquad (1)$$

where

$$\Delta a = f(C_1 N_{nz1} + C_2 N_{nz2} + \ldots\ldots) \qquad (2)$$

that is, Δa is a function of the number of occurrences of several load factors.

Program 2/Generalized Method: In this method, the μP system is used to perform a cycle-by-cycle crack growth analysis for a single generalized control point. The output data are the generalized crack length and flight time, and these data are used in the onboard μP to calculate the equivalent crack length for all other control points based on an equivalent DTA method.

Program 3/Multiple Control Point IAT System: In this system five control points, representing all major airframe components, are analyzed by means of a cycle-by-cycle crack growth program. Additional data similar to that produced by the above two programs are also output. All IAT crack growth computations are done onboard the aircraft.

Description of the Multiple Control Point IAT System

In the following sections the most extensive IAT system developed, the Program 3/Multiple Control Point IAT System will be described in greater detail.

A variety of documentation data are input to or computed by the IAT μP system during the course of operations. These data are:

(1) Aircraft serial number

(2) Date

(3) Home base

(4) Sequential flight number

(5) Time of day for the take-off

(6) Mission Type code number

(7) Gross take-off weight

(8) Current cumulative flight hours

(9) Flight time

(10) External store configuration

Of the above ten data items, the mission type code, the gross take-off weight, and the store configuration are input by the crew chief prior to each flight. There are thirty eight different mission types which may be selected. The remaining data items either are input when the IAT μP system is first activated or are calculated during operations. All of these data items can be revised by using the data transfer ground unit as an input device.

In order to permit calculation of time remaining to major events (inspection and/or critical crack length), the predicted crack growth history for each control point, based on the DADTA analysis [12,13] using an assumed service load history, is input and stored in memory. These data are stored as polynomial equations.

IAT Input Parameters

In the current A-10A STEMS™ system, the input parameters required to determine the stresses for the various control points are (1) normal load factor, (2) airspeed, (3) lateral load factor, and (4) gross weight. Typical stress-to-usage parameter relationships are:

(1) *For the wing front spar control point*

$$S = K_1 W n_z + K_2 n_z + K_c V^2 \qquad (3)$$

(2) For the engine nacelle pylon lug control point

$$S = K_4 n_z + K_5 n_z V^2 + K_6 V + K_7 n_z W + K_8 n_z W^2 + K_9 \qquad (4)$$

(3) For the inboard wing control point

$$S = K_{10} n_z W + K_{11} n_z \qquad (5)$$

where

W = the current aircraft weight
V = airspeed at the peak or valley of the load factor
n_z = the normal load factor

The K_i values are determined by regression analysis from data obtained from the L/ESS program (if available) or by analytic methods. For the inboard wing control point, the stress is defined as

$$S = (0.1667)\ n_z\ W + (-1137.0)\ n_z \qquad (6)$$

with

W = current aircraft weight in pounds

S = current stress in KSI

n_z = current normal load factor

No other usage data, with the exception of elapsed flight time, are required. The aircraft's weight is determined indirectly. Prior to flight, the crew chief inputs, via an annunciator button, the upcoming mission type code and the TOGW. These data are stored in the STEM™ system. Thereafter, an aircraft weight algorithm is used to calculate the instantaneous gross weight at any time in the flight by accounting for fuel usage, external stores ejection, and ammunition usage. The external storage ejection at each store station is electronically sensed. However, since the system has no knowledge of the actual store weight, a typical store weight has been assigned for each mission type and each store station, and this weight value is subtracted from the TOGW. In a similar manner, the gun firing is electronically sensed, and because of the unusual weight of the ammunition, the expended weight is estimated based on the duration of gun firing and subtracted from the TOGW.

All structural input usage parameters are read eight times a second. Events such as external store ejection and gun firing are sensed or read at occurrence. All data are temporarily stored until a load valley and a load peak are sensed, at which time the valley/peak input parameters are used to calculate the new valley/peak stresses for each control point being tracked. The system also contains a long term memory for storing exceedance data for load factors and stress.

In addition to the usage parameters, a variety of material properties and related geometrical data are stored semipermanently in the μP system memory and used, as necessary, by the cumulative crack growth program. These data are:

(1) Initial crack size; for example, crack width and depth for a quarter circle corner crack

(2) Normalized stress intensity coefficient relationship for $\alpha = K/\sigma$

(3) The Forman equation relating the incremental crack growth to ΔK, R, K_c and other constants

(4) The plastic zone equation

(5) The Wheeler retardation relationship and

(6) Time remaining to the next inspection.

Note that the initial crack size for all but two control points is 0.050 inches. The two control points which are different have initial crack sizes of 0.005 inches.

For each cycle of calculations occurring due to usage, the following parameters are also stored for use as input data for the next calculation cycle:

(7) Current crack size (a_i),

(8) Current time in flight hours,

(9) Current number of flights,

(10) Current plastic zone size and crack length (a_{pi}) for retardation effects and

(11) Time remaining to the next inspection.

Cumulative Crack Growth Program

The cumulative crack growth program used for the A-10A IAT program is a cycle-by-cycle crack growth analyses based on the Forman equation using the Wheeler retardation model. The program is discussed below and illustrated in Figure 6 for a typical control point (in this case, a wing control point).

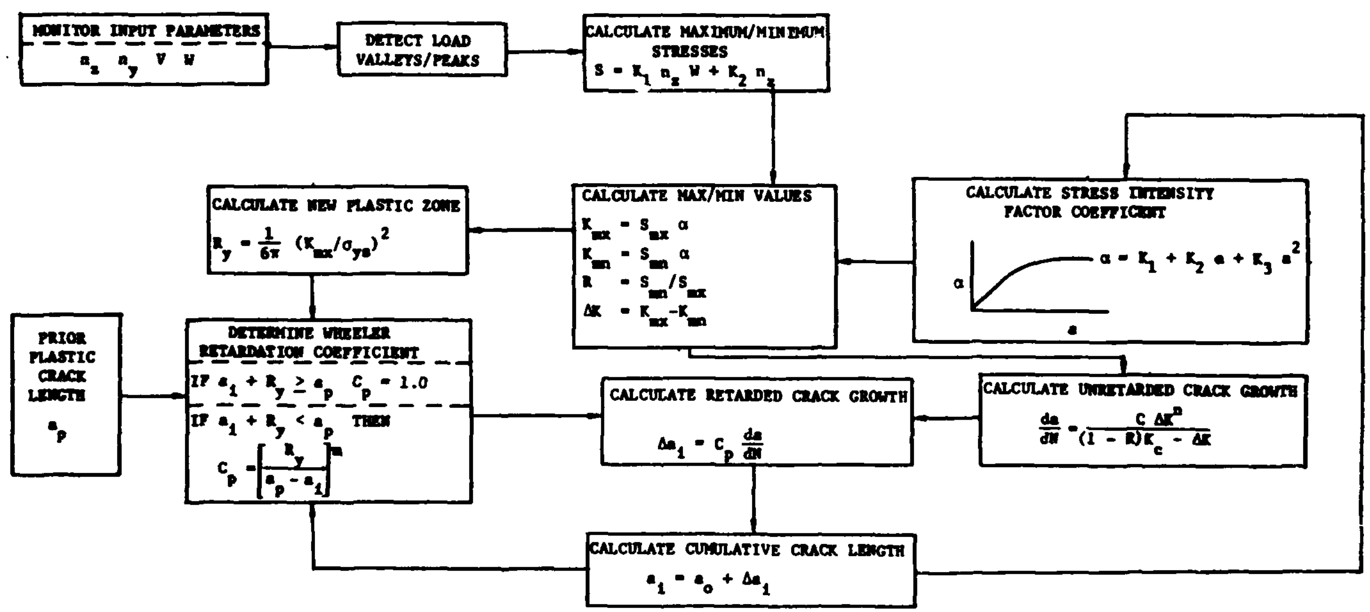


Figure 6. Cycle-by-Cycle Crack Growth Analysis Used on the Northrop STEMS™ Microprocessor Unit on the A-10A Attack Aircraft IAT Evaluation Program

STEP 0:

Prior to the start of the cycle-by-cycle analysis, the program memory contains the following data:

(1) External usage parameter-to-stress equations for all control points

(2) Material properties

(3) The anticipated crack growth curve (in polynomial form) with time to critical length, time to first inspection, etc., based on the anticipated life-time usage

(4) Geometrical data

STEP 1:

Assuming a prior overload, the current starting plastic zone size is calculated from

$$R_{y(i-j)} = 1/6\pi \left[K_{mx(i-j)}/\sigma_{ys} \right]^2 \tag{7}$$

where

$K_{mx(i-j)}$ = a previous maximum SIF defining the current overload plastic zone which occurred at the (i-j) cycle.

σ_{ys} = The yield strength

STEP 2:

The current combined overload plastic zone size and crack length ($a_{p(i)}$) is calculated from

$$a_{p(i)} = a_{(i-j)} + R_{y(i-j)} \tag{8}$$

where

$a_{(i-j)}$ = crack length associated with the (i-j) overload cycle

$R_{y(i-j)}$ = the overload plastic zone

$a_{p(i)}$ = some times referred to as the plastic crack length

STEP 3:

A new load cycle is applied. Calculate the new minimum (valley) and maximum (peak) stresses for the new load cycle (i).

$$S_i = (0.1667) n_{z(i)} W_i + (-1137.0)\, n_{z(i)} \tag{9}$$

where

S_i = new maximum or minimum stress (KSI)

W_i = new aircraft weight (lbs)

$n_{z(i)}$ = normal load factor

STEP 4:

From the previous crack length, calculate the value of the normalized stress intensity factor $\alpha = K/\sigma$. For this case

$$\alpha_i = (0.165) + (32.59)\, a_{(i-1)} - (428.6)\, a^2_{(i-1)} \tag{10}$$

where

$a_{(i-1)}$ = old or previous crack length

α_i = the new normalized SIF

STEP 5:

Calculate the new maximum and minimum SIF's, ΔSIF, and the stress ratio R from

$$K_{mx(i)} = S_{mx(i)} * \alpha_i \quad (11)$$

$$K_{mn(i)} = S_{mn(i)} * \alpha_i \quad (12)$$

$$\Delta K_i = K_{mx(i)} - K_{mn(i)} \quad (13)$$

$$R_i = S_{mn(i)}/S_{mx(i)} \quad (14)$$

STEP 6:

Calculate the new plastic zone size for the new load cycle (i+1) using

$$R_{y(i)} = 1/6\pi(K_{mx(i)}/\sigma_{ys})^2 \quad (15)$$

STEP 7:

Compare the crack length plus the new plastic zone size for the previous overload plastic zone size and crack length $(a_{p(i-j)})$.

if $a_{(i-1)} + R_{y(i)} \geq a_{p(i-j)}$

then $C_{p(i)} = 1.0$ (16)

if $a_{(i-1)} + R_{y(i)} < a_{p(i-j)}$

then $C_{p(i)} = (R_{y(i)}/(A_{p(i-j)} - a_i))^m$ (17)

where

m = 3.0 (Wheeler exponent for this material)

STEP 8:

Calculate the new incremental crack growth for the load cycle (i)

$$(da/dN)_i = (C\Delta K_i)n/[(1-R_i)\ K_c - \Delta K_i] * C_{p(i)} \tag{18}$$

where for this case,

C = 1.799E-07

N = 3.201

K_c = 83.0 KSI in.

STEP 9:

Compute the new cumulative crack length, where

$$a_i = a_{(i-1)} + (da/dN)_i \tag{19}$$

Note that the program continues to track the retarded crack lengths as the crack grows through the overload plastic zone so that it is always known when the old overload plastic zone is penetrated by a new crack length and its plastic zone size. When the old plastic crack length is penetrated, a new plastic zone size and crack length is calculated and stored along with the current crack length.

STEP 10:

Using the DADTA predicted crack growth curve equations (crack length versus flying hours), the current crack length is compared with the predicted crack length and an equivalent flying time is obtained (See Figure 7). Based on this equivalent time expended, a time-remaining to inspection/failure is computed with the inspection/failure times being based on the original DADTA predicted crack growth history.

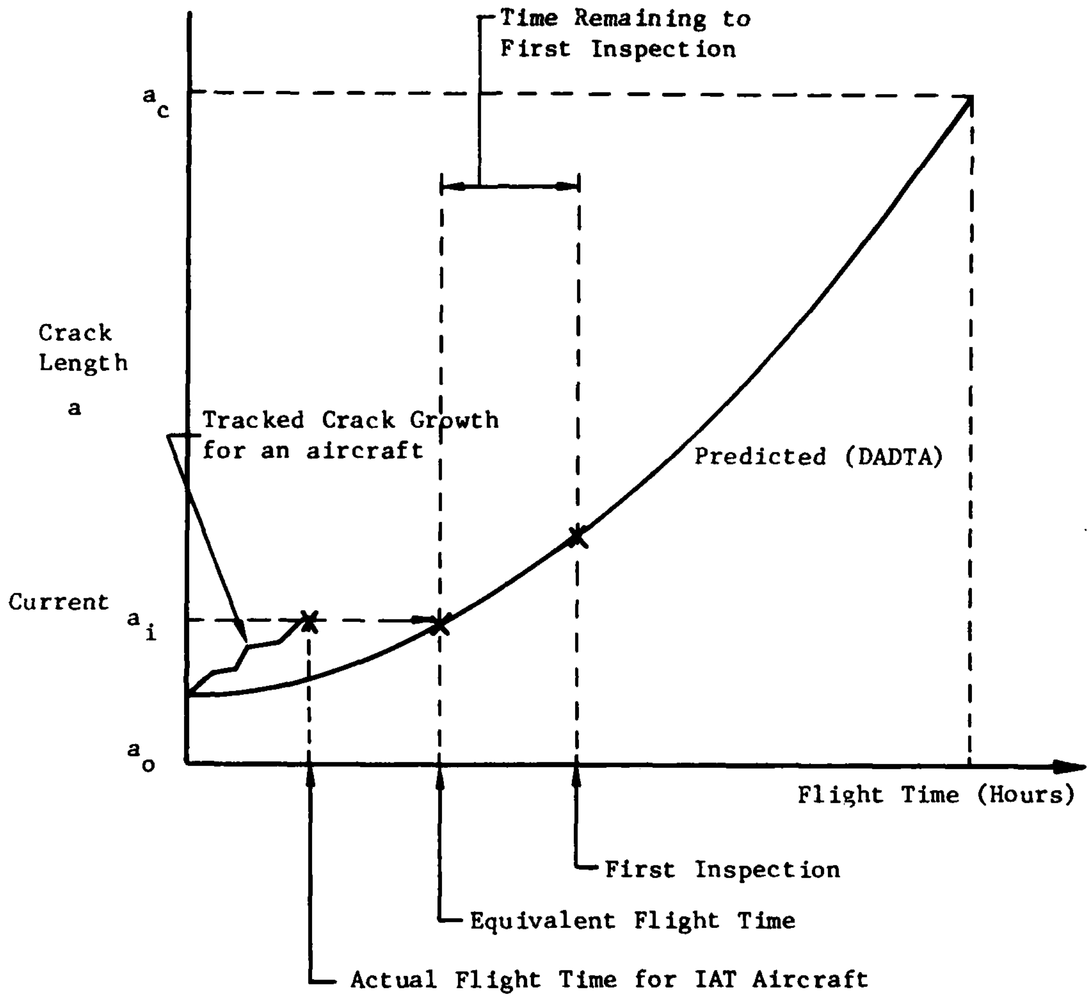


Figure 7. Method of Determining Time Remaining to Inspection for a Typical Crack Length Reported Via IAT Program Using DADTA Predicted Crack Growth Curve

STEP 11:

All intermediate IAT data are stored in memory for use in the next load cycle calculation. The data items are: (1) new crack length, (2) current plastic crack length, (3) elapsed flight time, and (4) flight number.

STEP 12. The computer program returns to Step 1 for the next load cycle.

IAT Output Parameters

All output parameters are temporarily stored in the μP memory until the ground data retrieval unit is used to off-load the data. The data retrieval unit serves as a temporary data storage until the data are transcribed onto a floppy disk and/or printed out on paper. The floppy disk is the medium for transferring the data to the central data processing center (ASIMIS). The data are normally retrieved at the end of each day of operations. The μP memory can store data for three flights, but if the data are not retrieved after each third flight, some minor flight-specific data will be lost. The output data will include: (1) aircraft documentation data (as described above), (2) current crack length for all control points, and (3) current time remaining to inspection for all control points.

L/ESS Output Data

The STEMS™ IAT program described here has the capability to collect and output three sets of L/ESS data and subsidiary data. The three L/ESS data sets are (1) a normal load factor (n_z) cumulative exceedance table, (2) a lateral load factor (n_y) cumulative exceedance table, and (3) a cumulative stress exceedance table for four structural control points. In addition, the maximum and minimum normal load factor values, the maximum airspeed, the maximum altitude, the total number of positive normal load factor occurrences, the cumulative flight time categorized by mission type, and the percent of total flight time by mission type will be collected, stored, and output for each flight.

The normal load factor data set is divided into eight load factor bands, while the lateral load factor data set is divided into ten (five positive and five negative) load factor bands. The stress exceedance data set is divided into twelve bands which cover the anticipated stress range from the greatest compression stress to the greatest tensile stress. The data can be retrieved after each flight, and the ground based retrieval unit has the capability to normalize all three exceedance tables to 1,000 flight hours.

Obviously, the above L/ESS data can be used to verify the predicted composite mission mix spectra. Since the data are not categorized by mission type, it cannot be used to verify the crack growth effects of each type of mission. In addition, some of the above data can also be used as IAT input data.

2. Case Study: LTV A-7D Attack Aircraft

Background

The IAT approach used on the A-7D attack aircraft may be categorized as one which directly determines the remaining crack growth or damage index using a relationship derived by means of a regression analysis. The IAT approach is described in References 4 and 5. The development of the basic loads is described in References 6 and 16.

A study of the references indicates that a considerable amount of work, both analytic and experimental, must be done to develop the final regression relationship between the damage index and the input usage parameters. Furthermore, several assumptions are necessary to permit all structural control points to be monitored from only one tracked generalized control point. The assumptions are:

(1) By using normalized crack growth curves, the crack growth at one location can be related to the crack growth at another location by means of the ratio of the two operational limits (usually critical crack length).

(2) When two aircraft experience two different load histories for the same structural control point, the crack growth under one load history can be related to the crack growth under the second load history by using normalized crack growth curves based on the ratio of the operational limits for the two load histories.

(3) A number of structural control points experiencing a variety of conventional usage load histories must have normalized crack growth curves which fall within a narrow envelope, thus allowing one curve to represent all cases with little error.

All of the above assumptions present potential problems as discussed below and in Reference 17.

Description of the Regression Analysis

The regression equation relates the damage index (DI) for the control point to flight time in hours and the number of load factor exceedances for four different but specific load factor values.

$$DI = C_o T + C_1 N_{g_1} + C_2 N_{g_2} + C_3 N_{g_3} + C_4 N_{g_4} \quad (20)$$

where

DI = the damage index for the time period being analyzed

C_i = constant coefficients previously determined by regression analysis

N_{g_i} = the number of load factor exceedances of the i^{th} load factor for the time period

T = the time period in flight hours

To determine the coefficients (C_i) a series of tests using a variety of load histories was performed on a number of specimens with similar geometries.

As a result of each crack growth test, the applied simulated flight time, the number of applied load factor exceedances for the specified load levels, and the resulting damage indexes (equivalent to the baseline load history operational limit) were determined. These data were then used in a regression analysis to determine the C_i values. Reference 4 indicates that the load factor level values for the regression equation are 5g, 6g, 7g, and 8g.

At any time during the IAT program, the total flight time and load factor exceedances (at the specified levels) for a specific aircraft are reported and used in the above relationship to calculate the damage index to date. Since this DI is for the generalized control point, the DI at other control points must be determined by the ratio of the operational limits. As indicated, if the current cumulative exceedance data are used then the damage index is the total damage index to date.

This method accounts for crack growth retardation or acceleration implicitly, because these effects are incorporated in the test results used to define the regression equation. However, since retardatation/acceleration effects are highly sensitive to the actual local stress history imposed on the various structural details, it is difficult to estimate the impact of these effects on secondary control points which are indirectly tracked via the generalized control point. The retardation/acceleration phenomena, as implicitly demonstrated in the testing of the generalized structural control point specimen, can only be related to the retardation/acceleration phenomena effects for the secondary structural control points by the use of additional data generated by the fatigue testing of the secondary structural control points.

IAT Input Parameters

For the A-7D program, the input parameters, other than the documentation parameters, are: (1) cumulative flying time in hours, (2) number of exceedances for four different load factor levels, (3) the coefficients for the damage index regression equation, and (4) the operational limit ratios needed to relate damage at the generalized control point to damage at the secondary control points.

IAT Output Parameters

This type of program has a small number of output parameters which are: (1) documentation parameters, (2) aircraft cumulative flight time, (3) cumulative and incremental damage index for the generalized and secondary control points, and (4) time expended or time remaining to an operational limit for all the control points.

3. Case Study: MCAIR F-4 Fighter

Background

The IAT programs for the F-4 fighter and the A-7D aircraft are very similar although there are differences in the parametric analysis methodologies [5,8,17,18,19] which support each IAT program.

The F-4 IAT program had used a Miner's Rule type of IAT fatigue analysis based on statistical accelerometer data. Over 3.5 million flight hours of this type of data were available. In addition, more than 40,000 flight hours of VGH data were available and the combined amount of data undoubtedly contributed to the reliability of the DTA. For the F-4 force, three spectra - mild, baseline, and severe - and a reliable means of identifying the severity of any given load factor spectrum were developed.

Description of the Parametric Analysis

The usage/input parameter common to all control points on the F-4 airframe is stress and the common output parameter is the damage index value resulting from the application of stress cycles. Thus the rationale behind the parametric analysis is to relate applied stress peaks to the crack growth damage index. In other words, since a statistical accelerometer instrument is the sole source of data, a relationship between the normal load factor spectrum and the resulting control point stress spectrum was needed. For this aircraft, the control point stress was determined to be a function of normal load factor (n_z), airspeed, altitude, and gross weight.

For the generalized control point, the basic steps in the development of the parametric analysis for each of the three types of spectra (mild, baseline, and severe) are:

1. Generate a normal load factor spectrum from the recorded load factor statistical data.
2. From this load factor spectrum generate a stress spectrum.
3. Use the stress spectrum to generate a stress cycle history applicable for analysis and testing.
4. Test a series of specimens representing the generalized control point structure and obtain the crack size versus number of cycles curve.
5. Develop a normalized crack growth curve.
6. Repeat the above process for the secondary control points so as to determine the relationship between the Damage Indexes (DI) of all of the control points.
7. Determine the percentage of crack growth damage caused by each of a series of stress levels by fractographically examining the generalized control point specimens. It is assumed that certain regions of the crack growth surface (on the fractograph) can be reliably linked to certain stress levels.
8. Convert the above discrete percent crack growth data to a plot of cumulative crack growth damage versus percent limit load.
9. Select stress levels representing integer values of load factor (n_z = 3, etc.)
10. Determine the percent cumulative crack growth for each stress level.
11. Determine the incremental crack growth for each stress level (Table 2).
12. Calculate the damage index per 1000 flight hours.
13. Calculate the incremental damage index for each load level (Table 2).
14. Using the load factor exceedance curve used for the test, determine the number of applied cycles for each load factor level (Table 2).
15. Calculate the allowable cycles for each load factor level where:

$$N_a = \frac{\text{Number of applied cycles for } n_{z_i}}{\text{DI for } n_{z_i}} \qquad (21)$$

16. The so called "S-N" Tracking curves generated by this method (Table 2) are shown in Figure 8. This procedure is repeated for each spectrum type.

TABLE 2. DATA FOR GENERATION OF A "S-N" TRACKING CURVE (FROM REFERENCE 19)

n_z	n_z mid point	f (ksi)	f_{max} (ksi)	Cycles	Crack Growth (%)	ΔD.I.	N
3.0		11.4					
	3.5		13.1	5,530	7.5	0.0192	288,000
4.0		14.7					
	4.5		16.5	2,430	13.5	0.0344	71,000
5.0		18.3					
	5.5		20.2	1,140	28.0	0.0716	16,000
6.0		22.1					
	6.5		23.9	377	37.0	0.0947	3,980
7.0		25.7					
	7.5		27.1	55	12.1	0.0310	1,780
8.0		28.5					
	8.5		29.8	8	1.9	0.0049	1,630
						0.2558	

The data shown in Figure 8 permit the analyst to determine the number of allowable cycles (for crack growth) for any stress level within the domain of the data. The total crack growth damage is determined in a manner analogous to the Miner-Palmgren cumulative fatigue damage analysis. The "S-N" relationship can be reduced to a relationship between the damage index and the number of occurrences of four discrete normal load factors (see Reference 4, pp. 52-55). That is, it can be shown that for a selected usage spectrum the Damage Index (DI) relationship is

$$DI = C_1N_1 + C_2N_2 + C_3N_3 + C_4N_4 \tag{22}$$

where

C_i = constant coefficients related to the weighted effect of each load level on the percentage of damage.

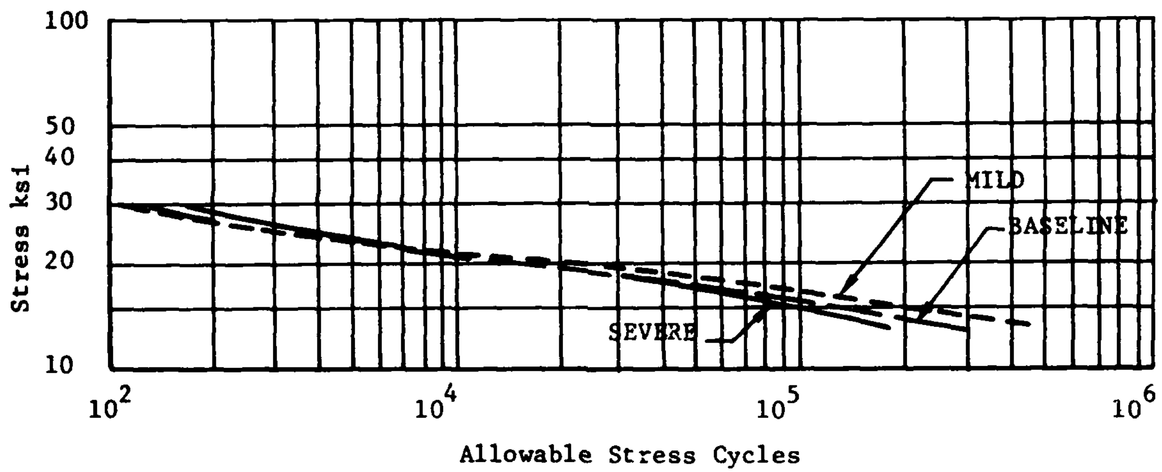


Figure 8. DTA Generated "S-N" Curves Used in The F-4 IAT Program (Reference 19.)

N_i = the number of applied load factor occurrences for the i^{th} load factor value.

IAT Input Parameters

The two usage parameters required are:

(1) The number of flight hours, so that the data can be normalized to 1000 flight hours, and

(2) The number of occurrences of applied normal load factors for the 3g, 4g, 5g, and 6g levels.

The severity of the usage spectrum is determined by examining the 5g exceedances per 1000 hours. For any n_z population sample, if there are more than 2200 exceedances per 1000 hours, it is a severe usage spectrum; for less than 2200 but more than 1100 exceedances per 1000 hours, it is a baseline usage spectrum; and if less than 1100 exceedances per 1000 hours it is a mild usage spectrum.

IAT Output Parameters

The basic output parameters are the aircraft flight time and the cumulative damage index for the generalized control point. Since the various operational limits (economical repair limit, inspection limit, failure limit) for all of the secondary control points are known in terms of their damage index relative to the generalized control point, only the knowledge of the current generalized DI and the aircraft's flight time are needed to determine the current DI for all points. The time remaining between the current damage index and the operational limit damage index must be estimated on the basis of an assumed future usage load factor spectrum (mild, baseline, or severe) and a projected flying rate.

SECTION VI

CASE STUDIES OF BOMBER/TRANSPORT CLASS IAT PROGRAMS

In this section, the existing and proposed IAT programs for the C-5A, C-141, CT-39A, and C/KC-135 transports are reviewed and discussed. The C-5A program is discussed in great detail because of:

(1) Its size in terms of the number of structural control points that are tracked

(2) The complexity of the crack growth analysis

(3) The vast scope and detail in its IAT output and FM data program

(4) The technical approaches used for several important stress analysis problems, and

(5) Its applicability as a typical large class aircraft IAT program.

The C-141 IAT program is also discussed in detail for many of the above reasons, and it serves as the basis for the advanced concept generic IAT system discussed in Section VIII.

1. Case Study: Lockheed C-5A Transport

Background

The C-5A IAT program [20,21,22,23] is the most extensive program currently in operation because of the nature of the crack growth analysis and the number of fracture control points tracked. The initial (or basic) method was a non-parametric method wherein each flight was subject to a cycle-by-cycle crack growth analysis based on stress spectra generated for each mission segment. The calculation of point stresses was complicated by the use of five different loading conditions, due to fuel flow sequencing and passive/active load distribution control system usage during the life of the individual aircraft. Table 3 summarizes the loading configuration history.

The total number of different mission segments is quite large and for many segments, the fracture damage is very sensitive to secondary usage parameters such as cargo weight, fuel weight, etc.

The current (alternate) method can be catagorized as a parametric analysis wherein precalculated crack growth tables are related to mission type. Therefore, the only usage parameter required is the identification of a predefined standard mission type. A small percentage of the missions flown (less than 15 percent) will probably not be able to be identified as a standard mission type and will therefore be analyzed using the brute force basic technique.

Outline of the Non-Parametric Crack Growth Tracking Approach

Basic Loads

The basic load data used to construct segment by segment mission stress histories were developed from a service loads recording program and a dynamic response test program. Included were the effects of the aircraft's active and passive lift distribution control systems and the alternate and standard fuel usage sequencing methods. The impact of the above items resulted in five different loading configurations being used during the life of each aircraft.

TABLE 3. C-5A TRANSPORT LOADING CONFIGURATIONS

Configuration	Time Span
Standard Fuel Sequencing (SFS) No Load Distribution Control	First flight to 15 February 1972
SFS and Passive Load Distribution Control System (PLDCS)	15 February 1972 to ALDCS incorporation date
Active Fuel Sequencing (AFS) and PLDCS	1 January 1974 to ALDCS incorporation date
SFS and Active Load Distribution Control System (ALDCS)	ALDCS incorporation date to present
AFS and ALDCS	Same as Above

The total load environment was divided into three classes: ground loads, gust air loads, and maneuver air loads.

Usage Data

All aircraft usage data are obtained from the flight usage log which is prepared by a crew member for each flight. Figure 9 is a sample of the form. The ASIMIS computer facility at OC-ALC processes the usage log and produces a "Combined Usage Format" flight description which is written on magnetic tape along with other flight records. These data are further processed to: (1) determine the type of each segment in the flight, (2) expand single segments into multiple segments if required to more accurately match the mission profile loading conditions, (3) determine segment incremental time periods, number of events, and configuration, (4) calculate fuel weight, Mach number, and altitude as needed to further characterize a segment, (5) insert dummy segment(s) for flap configuration, (6) insert Air-Ground-Air (AGA) segment(s) after each touch-and-go (TAG) landing, (7) designate segment codes such as runway roughness, contour flying ride setting, maneuver load equation, phase type stress spectra, load source for standard segments, and (8) construct flight header I.D. data such as flight sequence number, log number, flight duration, mission type I.D., configuration, number of mission segments in the flight and aircraft serial number. A typical usage mission type profile is shown in Figure 10.

At this point in the IAT analysis, two choices are possible. First, in the basic method, the mission type profile can be used to construct a stress spectrum for each segment and to assemble the segmental stress histories into a flight stress history. This flight-by-flight stress history is then analyzed using a cycle-by-cycle (or grouped cycle) cumulative crack growth program. In the second (alternate method) choice, only the mission type identity and other characterizing usage parameters are needed, since the incremental crack growth has been parametrically calculated for each mission type versus key usage parameters.

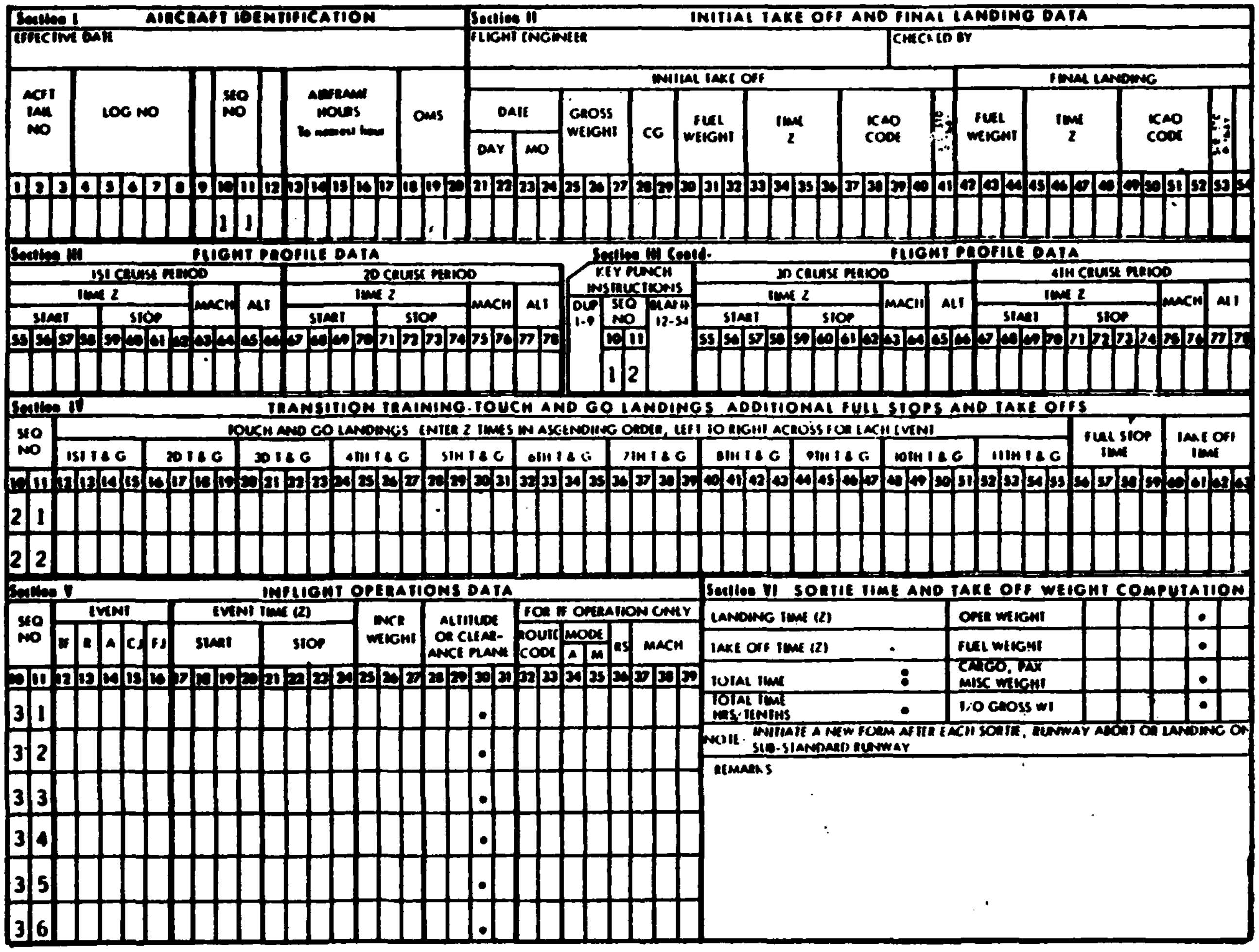


Figure 9. Flight Usage Log for C-5A Transport Aircraft (MAC FORM 89)

<u>Basic Profile - Training Mission</u>

HEADER INFORMATION

SEQ. NUM.	SERIAL NUM.	LOG	64-MISS. NUM.	DATE	CONF.	FLT. HRS.	15-MISS. NUM.	NUM. SEGMENTS
38	700465	78003A	2	22-1-78	5	1.4	11	24

FLIGHT PROFILE

SEG. TITLE	SEG. NUM.	L.S.	RR,RS or EQ.	PT	(EVTS.) or TIME~MIN.	FUEL	CARGO	MACH or VEL.	ALT.	RUNWAY or CONFIG.
RAMP	1	21	1	5	.0	109400.	32000.	.00	0.	
TAXI	2	21	1	5	7.5	108700.		15.0	0.	STD.
TAKEOFF	3	22	1	7	(1.0)	107500.		.00	0.A	STD.
CLIMB-A	4	17	5	11	.0	106600.		.200	250.	APPROACH
CLIMB-B	5	11	5	11	.0	106600.		.250	1250.	CLEAN
TRAFFIC	6	17	8	11	32.0	101700.		.228	2000.	APPROACH
TOUCH & GO	7	24	1	8	(1.0)	96800.		.0	0.	STD.
AIR-GROUND-AIR	8	29	8	9	(1.0)	96800.		.228	2000.	APPROACH
TRAFFIC	9	17	8	11	5.0	96100.		.228	2000.	APPROACH
TOUCH & GO	10	24	1	8	(1.0)	95300.		.0	0.	STD.
A-G-A	11	29	8	9	(1.0)	95300.		.228	2000.	APPROACH
TRAFFIC	12	17	8	11	20.0	92300.		.228	2000.	APPROACH
TOUCH & GO	13	24	1	8	(1.0)	89200.		.0	0.	STD.
A-G-A	14	29	8	9	(1.0)	89200.		.228	2000.	APPROACH
TRAFFIC	15	17	8	11	12.0	87400.		.228	2000.	APPROACH
TOUCH & GO	16	24	1	8	(1.0)	85600.		.0	0.	STD.
A-G-A	17	29	8	9	(1.0)	85600.		.228	2000.	APPROACH
DESCENT-A	18	17	7	11	.0	85600.		.271	2000.	APPROACH
TRAFFIC	19	17	8	11	15.0	83300.		.228	2000.	APPROACH
DESCENT-B	20	17	7	11	.0	81000.		.212	1000.	LANDING
PRE-TOUCHDOWN	21	17	7	11	.0	81000.		.215	0.	LANDING
FULL STOP	22	24	1	18	(1.0)	81000.		.0	0.	STD.
ROLLOUT	23	23	1	6	(1.0)	81000.		.0	0.	STD.
TAXI	24	21	1	5	7.5	80500.		15.0	0.	STD.

Notes: 1. <u>RR</u>, <u>RS</u> or <u>EQ</u> = codes for Runway Roughness, Ride Setting or Maneuver Equations - directs the logic in the spectra program to the proper location to read criteria.

a. Runway Roughness - Applicable to taxi, takeoff, rollout, full stop, touch-and-go segments.

1 = Standard runway
2 = Substandard runway

b. Ride Setting - Applicable to contour flying segments

a. Runway Roughness - Applicable to taxi, takeoff, rollout, full stop, touch-and-go segments.

1 = Standard runway
2 = Substandard runway

b. Ride Setting - Applicable to contour flying segments

1 = Soft ride
2 = Normal ride
3 = Hard ride

c. Maneuver Equation - Applicable to traffic, climb, cruise, descent, airdrop, fuel offload, cargo offload segments

1 = Design spectrum
2 = Logistics climb
3 = Logistics cruise
4 = Logistics descent/traffic
5 = Training climb
6 = Training cruise
7 = Training descent
8 = Training traffic (also used for composite < 3000 feet)
9 = Composite non-traffic (used for > 3000 feet)

2. <u>PT</u> = Phase Type - directs the logic in the spectra program to the proper location to read stresses.

1 = Flight (ordinary)
2 = Contour flight
5 = Taxi
6 = Rollout
7 = Takeoff
8 = Landing Impact
9 = A-G-A
11 = Traffic
12 = Aerial refueling

3. <u>LS</u> = Load Source

5 = Aerial refueling
7 = Contour flying
9 = Airdrop
11 = Climb
13 = Cruise
15 = Descent
17 = Traffic
21 = Standard taxi; 25 = Substandard taxi
22 = Standard takeoff; 26 = Substandard takeoff
23 = Standard rollout; 27 = Substandard rollout
24 = Standard impact; 28 = Substandard impact

Figure 10. Sample Mission Type Profile Based on Flight Log Data for a C-5A Transport

1

2

Stress History Development

The total stress history [20] for large aircraft like the C-5A is made up of three components: ground loads, gust loads, and maneuver loads. For ground loads the number of cumulative occurrences, $N_p(\Delta S)$, of the incremental stress value ΔS is determined from

$$N_p(\Delta S) = N_o T \sum_{k=1}^{r} P_k \ \mathrm{EXP}\left[\left(\frac{\Delta S}{b_k \sigma}\right)^2\right] \tag{23}$$

where

P_k = The percentage of time (T) spent on a runway (R) of roughness b_k

σ = The ratio of rms value of the aircraft's response to the rms value of the input

b_k = runway roughness intensity factor

ΔS = the incremental stress arbitrarily chosen

N_o = unit response of the aircraft in terms of frequency

To determine the stress history, the incremental stress (ΔS) is added/subtracted to or from the mean stress values derived from the design loading conditions.

Almost all of the above parameters must be measured or statistically derived on the basis of large amounts of load response data collected during actual aircraft service. Futhermore, the aircraft's response parameters (σ and N_o) are functions of cargo weight, fuel weight, fuel weight distribution or fuel flow sequencing, and ground speed, while other parameters are functions of the ground load environment.

The air loads due to air turbulence (gusts) are computed from the gust exceedance equation

$$N_p(\Delta S) = N_o T \left[P_1 e^{-\Delta S/b_1\sigma} + P_2 e^{-\Delta S/b_2\sigma} \right] \tag{24}$$

where

$N_p(\Delta S)$ = the cumulative number of cycles of incremental stress, ΔS

N_o = the aircraft's characteristic frequency of response to a unit rms gust velocity input

T = time spent in the segment

σ = the rms amplitude value in response to a unit rms gust velocity amplitude input

P_1 = percentage of time in non-storm turbulence

P_2 percentage of time in storm turbulence

b_1 and b_2 = composite rms gust velocity of the non-storm and storm turbulence respectively

As in the case of the ground loads, the unit aircraft response parameters - σ and N_o - are functions of the fuel weight and distribution, Mach number, altitude, cargo weight, and air load distribution due to the LDCS configuration.

For pilot induced maneuver loads, the incremental stress occurrences are computed from the maneuver exceedance equation:

$$N_P(\Delta S) = T\left[P_1 e^{-(\Delta G/b_1)(\Delta S/\Delta G)} + P_2 e^{-(\Delta G/b_2)(\Delta S/\Delta G)}\right] \qquad (25)$$

where

ΔG = the incremental normal acceleration factor at the aircraft's center of gravity,

$(\Delta S/\Delta G)$ = The analytical ratio of the incremental stress per incremental normal acceleration factor.

The other parameters in Equation 25 are analogous to the parameters in the previous equations. The P and b parameters are functions of mission type and mission segment and they are derived from maneuver air load data segregated by mission and segment type.

In summary, for all three load environments the major parameters determining the incremental and mean stress values are cargo weight, fuel weight and distribution, airspeed, ground speed, altitude, and the air load distributions which affect the load factor-to-stress transfer functions. Since these parameters will be different for different load environments, the parameters must be grouped by like conditions. In the case of the C-5A, the mission segment type is the selected method of grouping the usage loads.

To construct a flight spectrum, the individual mission segments and their characterizing parameters are identified and defined. For the given segment time interval, a mean stress (plus or minus a spectrum of incremental stress cycle amplitudes) history is assembled and arranged in a low to high amplitude sequence. The incremental stress amplitudes and occurrences are derived from the appropriate stress exceedance equations as explained above and in Reference 24. Each stress exceedance history is related to a particular structural location.

Interactive Stress Histories

For a number of fracture tracking locations on the wing it was necessary to develop two interactive stress spectra [References 20 and 24]. For example, critical fracture tracking locations on the wing skin plank spanwise splice were found to be affected by stress histories generated by the wing's dynamic response to gust loading in two independent response modes: normal wing bending and wing torsion.

Empirical data showed that the C-5A wing skin axial (spanwise) stress due to gust response is for the most part generated by normal wing bending moments which occur at a frequency different than the wing torsion frequency. For air turbulence air loads, the two external wing load distributions appear to be independent and random. The problem of combining the interactive stresses is important since the C-5A transport now uses a lift distribution control system which reduces the spanwise stresses due to normal bending but increases the spanwise shear stresses due to torsion. Because of the significant amplitudes of the secondary stresses, it was necessary to develop these two stress spectra independently and then to combine them in some realistic and practical manner. The phase relationship between the axial (spanwise) stresses caused by bending and the shear (spanwise) stresses caused by torsion varied according to mission segment, loading condition, tracking point location, etc., and had to be determined from the analysis of empirical data.

The C-5A IAT methodology used a large amount of L/ESS data to verify or determine the relative amplitudes of the two stress processes, their frequency, and their phase relationship. Although these two processes are random and independent, they are nevertheless stationary processes for any given parameter interval defined by aircraft weight, fuel distribution, altitude, airspeed, gust spectra, etc. Once a sufficiently large body of gust load response data are available for all intervals of the flight regime, no further data need be collected during the IAT program because the phenomena are strictly stationary processes. The only exception occurs if the aircraft is modified in a way so as to affect its dynamic response characteristics.

Pilot induced maneuver loads, on the other hand, are not random. Therefore, the relationship between the two interactive stress fields can generally be fully defined by analysis and test. The difficulty in this case is the effort required to analyze a sufficient number of maneuver load conditions so that the interactive stress or load envelope can be fully defined. The minimum number is the number of loading conditions/distributions required to define the loads for each of the standard mission segment types used to describe the aircraft's mission profile. Therefore, in the case of manuever load interaction, no special usage parameters are necessary and the usage parameters which define the mission segment and load distribution and amplitude are sufficient.

Crack Growth Methodology

Very little information has been published on the C-5A crack growth methodology and only a few basic features can be described here.

The method incorporates a crack growth retardation model and is essentially a cycle-by-cycle, flight-by-flight analysis. A computer cost comparison [Reference 20 p. 2.2-31] indicates that the cost of analyzing one structural area is 56 computer hours per a force of 77 aircraft or 0.73 computer hours per aircraft per structural area.

Outline of the Parametric Crack Growth Tracking Approach

Background

The non-parametric approach described above is a very detailed, complex, and expensive method. The need for cost savings and a quick turn-around for individual aircraft tracking analysis is obvious and can be met with a parametric type of IAT analysis provided the accuracy of the analysis does not suffer.

An "alternate approach" [20] was developed based on the concept that a finite set of mission types can be used to calculate crack growth damage and still provide the desired accuracy. Each mission type (say logistics) was divided into subtypes by cargo weight, duration of mission, types and number of landings, fuel weight, etc. A sensitivity study was performed using both the basic non-parametric analysis and the alternate parametric analysis to determine the relative accuracy, the relative importance of the various mission/flight parameters, mission segments, and mission types, and the importance of several crack growth parameters. The general method used in the sensitivity study was to perform a series of crack growth analyses for a few structural locations by varying the value of the parameter under study while keeping the other parameters constant. The parameter used as the yardstick of comparison was the crack growth per unit time at a certain crack length. This series of analyses was also repeated for variations in initial crack length and degrees of crack growth retardation. The results are discussed in the next section.

Impact of the Sensitivity Study

The types and number of parameters considered in the sensitivity study are listed in Table 4. Only the flight parameters can be considered as primary aerodynamic performance parameters. The others (mission type and mission segment type) are in effect combinations of the primary aerodynamic performance parameters.

Typical flight (primary) parameter sensitivity results are shown schematically in Figures 11 and 12. As was expected, high values of cargo weight produced the highest crack growth rate. When cargo weight is cross-correlated with fuel weight a more complex relationship is demonstrated. However the figures demonstrate the parametric effects for only one area of the wing structure. Therefore, even though some general conclusion may be drawn from these figures, program relibility will depend on all structural areas of significance being subjected to a sensitivity study because different structural areas may be sensitive to different primary parameters. Within certain limits, it can be assumed that large sections of the airframe will exhibit the same type of sensitivity. For example, the lower skin of the wing will be greatly affected

TABLE 4. TYPES AND NUMBERS OF PARAMETERS STUDIED

TYPE OF PARAMETER	PARAMETERS USED IN SENSITIVITY STUDY					
FLIGHT (PRIMARY) [2]	CARGO WEIGHT	FUEL WEIGHT	ALTITUDE	AIRSPEED		
MISSION SEGMENT TYPE	CLIMB	TRAFFIC	CRUISE	AERIAL REFUELING	DESCENT	TRANSITION (AIR-GROUND-AIR)
MISSION TYPE	LIGHT WEIGHT LOGISTICS	MEDIUM WEIGHT LOGISTICS	HEAVY WEIGHT LOGISTICS	TRAINING	AERIAL REFUELING	
CRACK GROWTH	INITIAL CRACK LENGTH	DEGREE OF CRACK GROWTH RETARDATION				

Note: 1 Data are from Reference 20.

[2] Flight (primary) parameters analyzed for specific mission segment(s), constant altitude, constant airspeed, and a specific initial crack length.

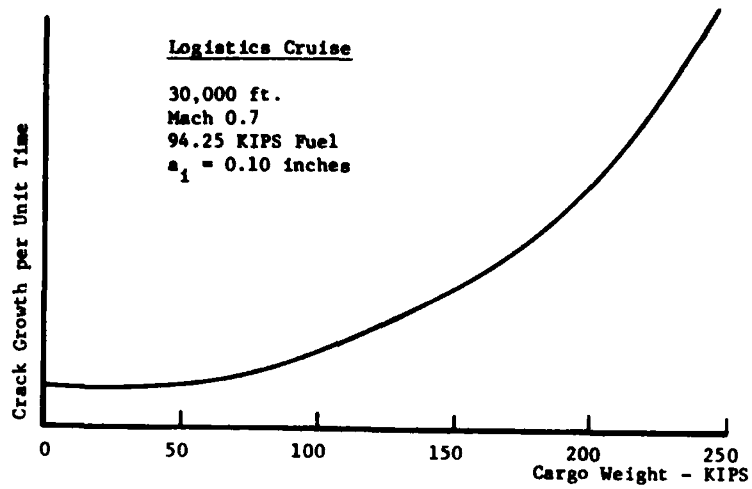


Figure 11. Effect of Various Cargo Weights on Crack Growth Rates for a Typical Location on the Inner Wing Lower Skin of a Transport (Reference 20)

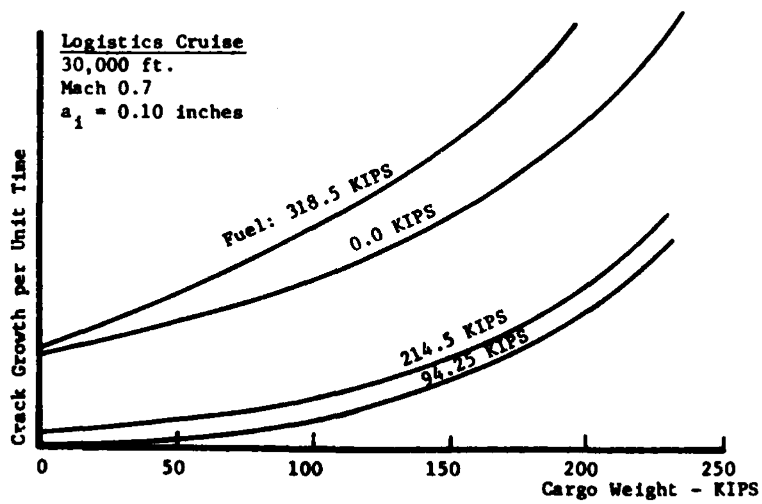


Figure 12. Effect of Variations in Two Parameters - Fuel Weight and Cargo Weight - On Crack Growth Rates for a Typical Location on the Inner Wing Lower Skin of a Transport (Reference 20)

by cargo weight. Fuel weight will have a similar but smaller effect. However, the outer wing lower skin will be more affected than the inner wing lower skin by the fuel weight parameter.

The parameter sensitivity must also be related to the number of occurrences or time duration of the parameter. The importance and effect of the time or occurrence factor can only be evaluated by examining a large amount of usage data. As an example, consider the cargo weight parameter-to-crack growth rate relationship shown in Figure 13 (a). As can be noted, the crack growth per unit time at a cargo weight of 250,000 lbs is about three times the crack growth rate for a cargo weight of 150,000 lbs. From actual or design usage data, shown schematically in part (b) of the figure, the number of times that certain cargo weights are planned to be transported has been plotted as units of time per the planned lifetime of the aircraft. The plotted data show that cargo weights in the regime above 200,000 lbs will seldom be carried compared to moderate cargo-weights in the 125,000 lbs to 175,000 lbs cargo regime. It must also be noted that this cargo weight population density per lifetime is only applicable for logistic types of missions. The cargo population density for training missions would probably look quite different. Part (c) of the figure shows how the relationship between the number of occurrences of a parameter and its intrinsic crack growth rate will result in different amounts of crack growth damage on the basis of time, whether it be the planned lifetime or a unit base of 1000 flight hours. If it can be reliably expected that a high percentage of logistic missions will carry moderate cargo weights, then that moderate weight regime should be more finely subdivided when the usage intervals are planned. However, the high cargo weight regime can not be safely ignored because of the high crack growth rate associated with it. Therefore, even though rate of the occurrence of high cargo weight missions is relatively low, it would improve the reliability of the analysis if the high end of the weight regime were also finely subdivided into small usage intervals. The conclusion is that for cargo weight parameters, their intrinsic crack growth rate factors, and their expected population density must be analyzed in order to plan the most effective cargo weight usage interval sizes. This conclusion can be generalized for almost any usage parameter.

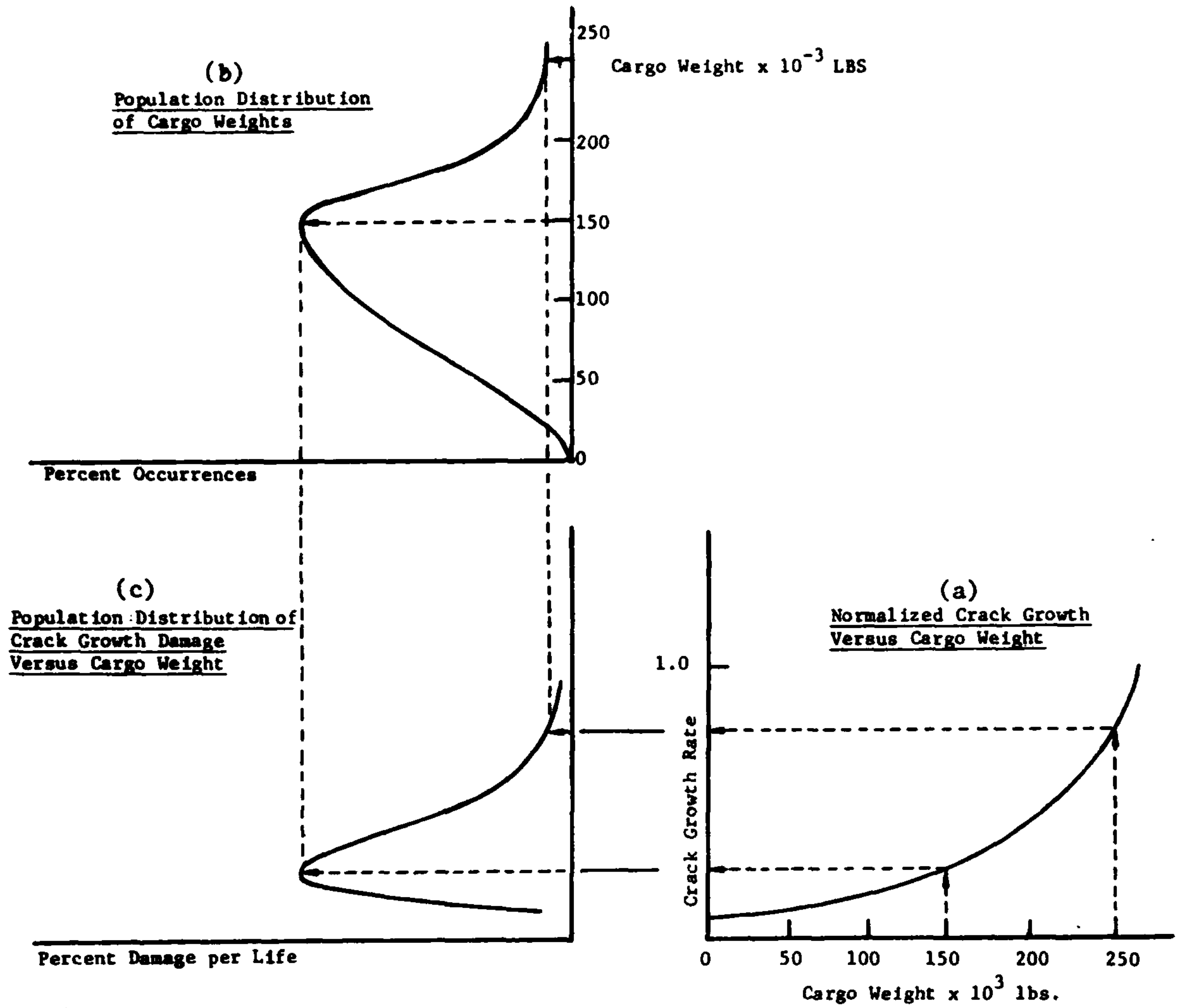


Figure 13. Effect of the Distribution of Occurrences of a Major Usage Parameter

In terms of the parametric IAT analysis, the subdivision of the cargo weight regime into X number of intervals means that X number of parametric analyses must be performed for the cargo weight parameter. If for example, an IAT analysis used only three usage parameters (cargo weight, fuel weight, flight duration) versus a number of mission types then the crack growth rate matrix would have four dimensions and the number of crack growth rate intervals would be

$$N_{CGR_i} = N_{CW} * N_{FW} * N_{FD} * N_{MT} \tag{26}$$

where

N_{CW} = Number of cargo weight intervals,

N_{FW} = Number of fuel weight intervals,

N_{FE} = Number of flight duration intervals

N_{MT} = Number of mission types

and N_{CGR_i} = number of crack growth rate cases.

If many of the above input/usage parameters had an excessive number of intervals, the number of parametric crack growth analyses would be unnecessarily large. On the other hand, if some of the input/usage parameter intervals were too few and coarse then the accuracy and reliability of the IAT analysis would suffer - especially if that input/usage parameter had a strong influence on crack growth. It follows from the above discussion that a parameter sensitivity study is necessary to identify the more important input/usage parameters and to determine the optimum sizes and numbers for the parameter intervals.

For the C-5A transport, Reference 20 indicates that the primary flight parameters are ranked according to their impact on crack growth rates as follows: cargo weight, fuel weight, altitude, and airspeed. The ranking held true for the five loading configurations created by the various combinations of

the three lift distribution control systems and the fuel flow sequencing systems even though the the actual crack growth rates changed in value. When the sensitivity study was applied to the mission type and mission segment type usage parameters, the results indicated that the amount of damage per mission/segment type was not generally related to the amount of time assigned to the mission segment type parameter (see Figure 14). These results indicate where and when the crack growth damage occurs. For example, because of the frequency of large loads, the aerial refueling segment results in exceptionally high crack growth rates. Therefore, even though the amount of mission profile time spent in the aerial refueling segment is little (upper left diagram of Figure 14) its contribution to the total crack growth is large (two lower left diagrams of Figure 14). In addition, although the cruise segment accounts for about 70% of the profile flying time (upper left diagram of Figure 14) it accounts for only a small percentage of the total crack growth because of the mild loading spectrum experienced during cruise. The distribution of crack growth by mission type shows similar relationships. The percentage of crack growth contributed by aerial refueling and training missions is disproportionally large compared to the time spent in those missions (right diagrams of Figure 14). The effect of structural location is also shown (lower two diagram pairs of Figure 14).

The two crack growth parameters reported (initial crack length and degree of retardation) showed no unusual behavior. Changes in these two parameters resulted only in uniform shifts in the crack growth rate curves.

It is believed that the general conclusions of the C-5A sensitivity study are of interest because they can serve as guidelines for the development of other large aircraft IAT programs. Refer to Table 5.

Mission Type Development

The method of developing and verifying the set of mission types is straight forward. Based on past knowledge and projections of future aircraft usage a set of segment-by-segment mission type profiles was developed. Within each

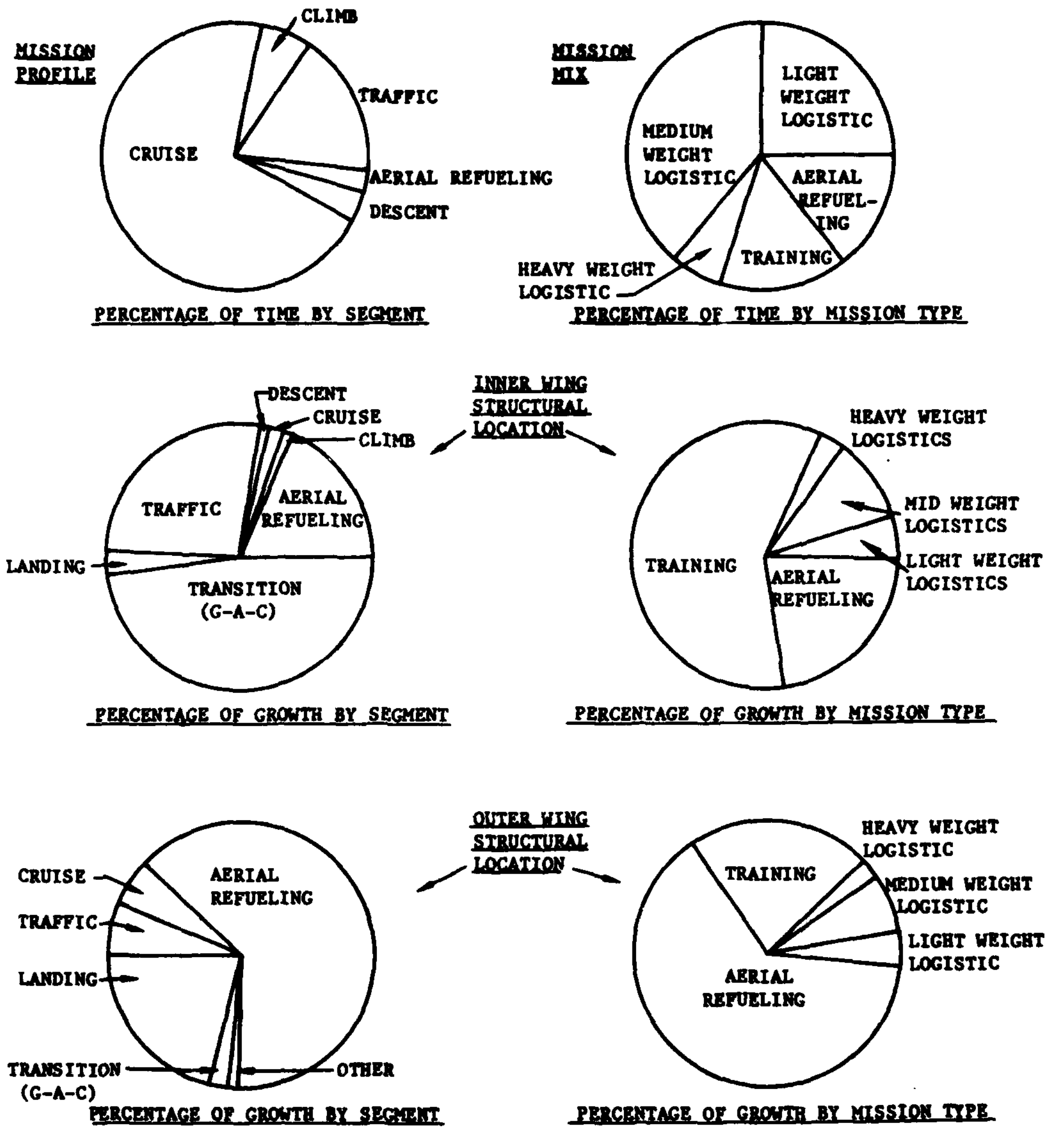


Figure 14. Percentage of Time and Crack Growth Distributions for a Selected Mission Profile and a Selected Mission Type Mix for an Inner Wing and an Outer Wing Structural Location

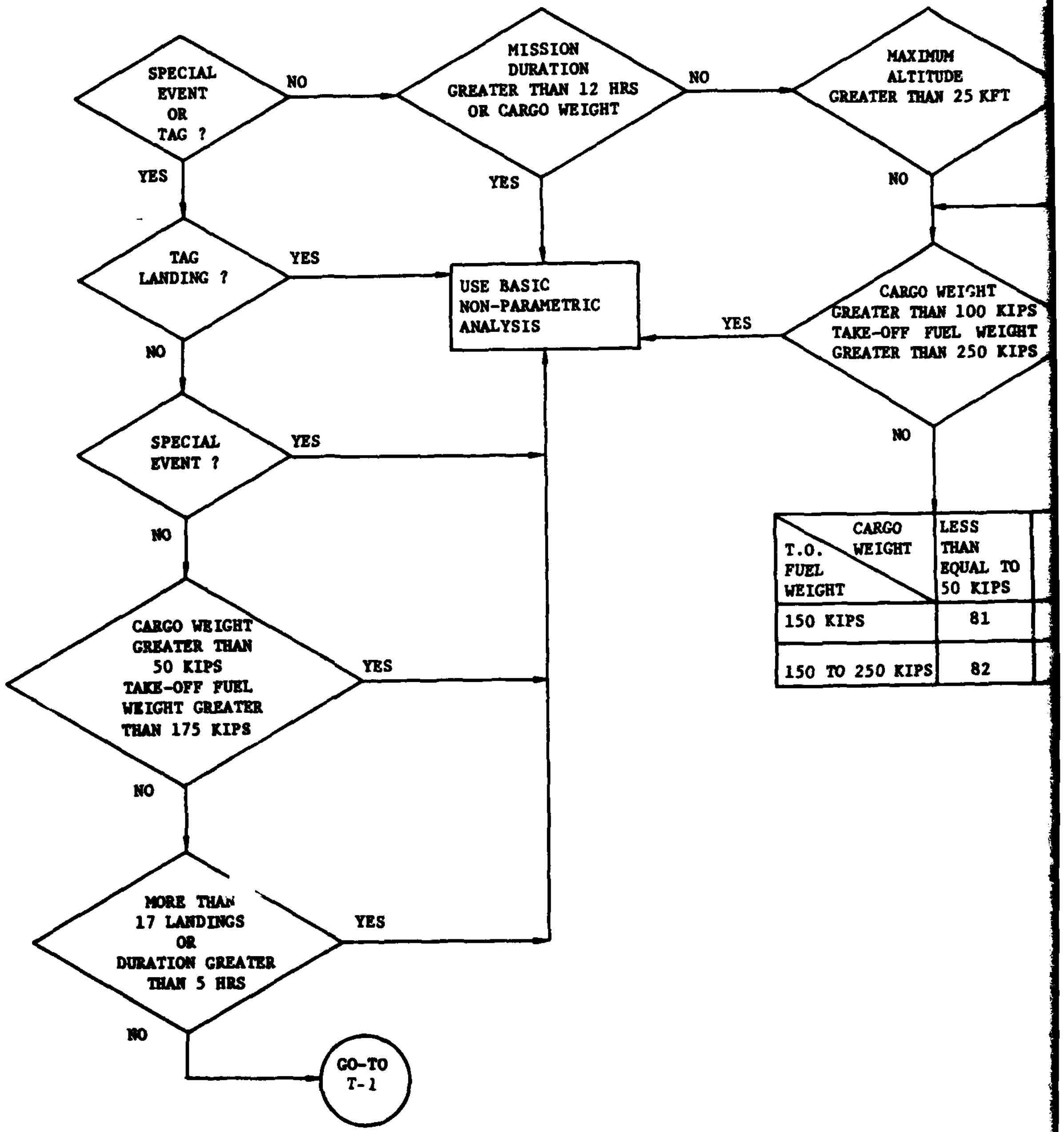
TABLE 5. GENERAL CONCLUSIONS OF THE C-5A USAGE PARAMETER SENSITIVITY STUDY

SENSITIVITY STUDY CONCLUSIONS	COMMENTS
Usage grouping by Mission Type is preferred over segment type or data block grouping.	Most effective in terms of computer cost effectiveness and simplicity.
All missions can not be predefined by a Mission Type.	Variations in actual flight data indicate that about 15 percent of flights must be analyzed individually outside the parametric IAT analysis for cost effectiveness.
Wing load distribution variations (due to load distribution control systems and fuel flow sequencing systems) must be accounted for.	Required for accuracy of analysis of past usage.
Missions and mission segments which cause extremely high damage rates (like aerial refueling) should be analyzed by the non-parametric approach.	Frequency of occurrence is low and will not cause excessive analytic costs.
Mission types must be defined so that the cargo weights and time spent in traffic segments are closely defined.	Cargo weight is the most critical parameter for logistic flights while traffic segment duration is critical for training mission.
The parametric IAT analysis method must be flexible enough to handle significant future usage changes in the force's mission.	Operational necessity.

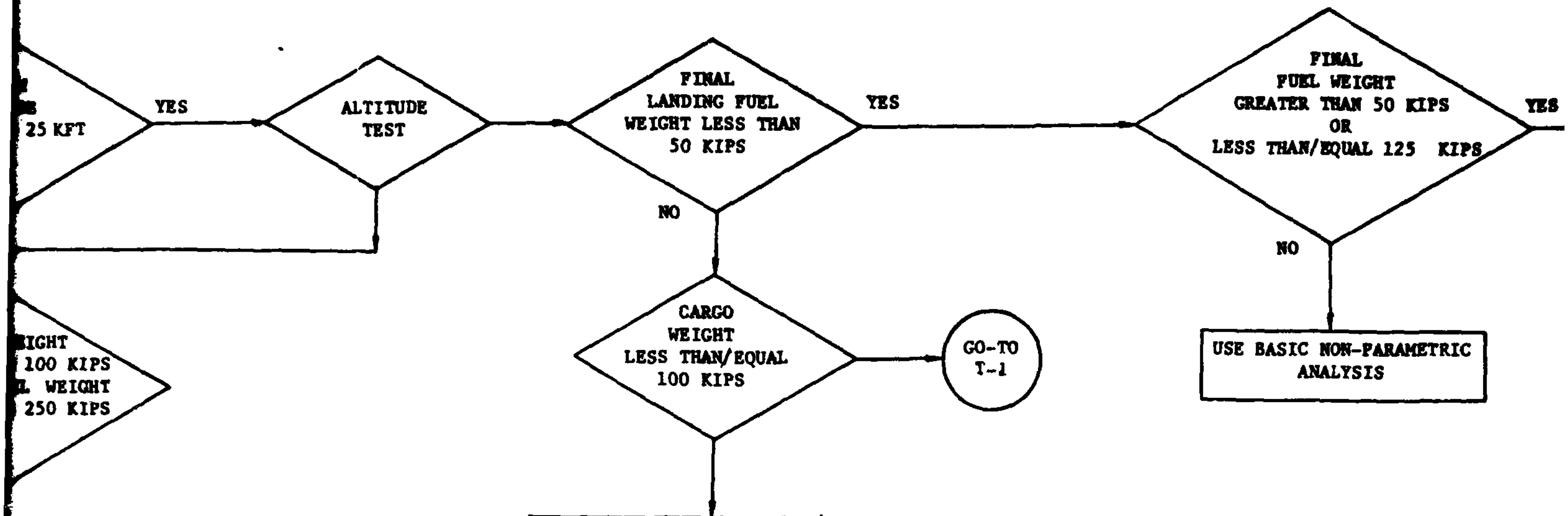
segment the load cycles were arranged in a low to high sequence. A linear (no retardation) cycle-by-cycle crack growth analysis was performed for several structural locations for each mission type using the same initial crack length. A sampling of actual USAF C-5A usage data was then used to verify the accuracy of the mission type definitions. The actual missions were first matched to a mission type and then analyzed in the same manner. The crack growth data for the actual flights were then compared to the crack growth data of the pre-defined mission types and evaluated. Where significant discrepancies existed, the mission was studied to determine the cause. Adjustments were made to the mission logic and the comparative analysis repeated until a satisfactory match was obtained. The size of the mission type set progressed from 62 types to 92 types and finally to 186 types. The changes were due to the necessary increase in the number of cargo weight and mission duration intervals. For example, in the 62 mission type classification logic, there were four mission duration intervals and five cargo weight intervals for the logistic missions. These catagories were expanded to seven mission duration and ten cargo weight intervals in the 186 mission type set.

The 186 mission set classification logic was further refined for the Force Status program [Reference 20, page 4.1-4] and a final set of 120 mission types was developed for the classification logic tree diagram. See Figure 15 for details. It was anticipated that about 15 percent of all flights would fall outside the limits of the classification logic. These undefined missions would be analyzed using the basic non-parametric analysis which constructs a more accurate segment-by-segment definition of the flight. There are two important justifications for this procedure: (1) these special flights represent an extremely damaging load environment and therefore a more accurate crack growth analysis is justified and probably necessary, and (2) certain types of missions are extremely difficult to stereotype by means of a classification logic decision tree diagram of practical size. Flights that are not classified by mission type are:

(1) Any flight containing a special event such as aerial refueling, airdrop, cargo jettison, fuel jettison, contour flying, or substandard runway use



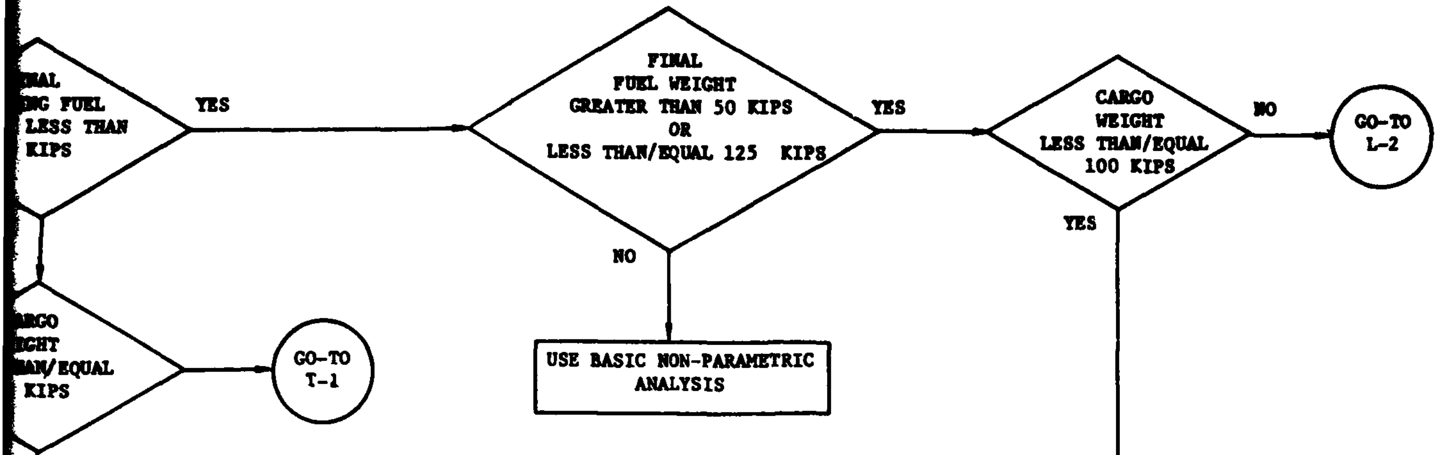
SPECIAL EVENT OR TAG ?
NO
MISSION DURATION GREATER THAN 12 HRS OR CARGO WEIGHT
NO
MAXIMUM ALTITUDE GREATER THAN 25 KFT
YES
YES
NO
TAG LANDING ?
YES
USE BASIC NON-PARAMETRIC ANALYSIS
YES
CARGO WEIGHT GREATER THAN 100 KIPS TAKE-OFF FUEL WEIGHT GREATER THAN 250 KIPS
NO
SPECIAL EVENT ?
YES
NO
NO
T.O. FUEL WEIGHT
CARGO WEIGHT
LESS THAN EQUAL TO 50 KIPS
150 KIPS
81
150 TO 250 KIPS
82
CARGO WEIGHT GREATER THAN 50 KIPS TAKE-OFF FUEL WEIGHT GREATER THAN 175 KIPS
YES
NO
MORE THAN 17 LANDINGS OR DURATION GREATER THAN 5 HRS
YES
NO
GO-TO T-1



ESS HAN QUAL TO 0 KIPS	50 TO 100 KIPS
81	83
82	84

DURATION (HRS) / CARGO WEIGHT	LESS THAN 3	3 TO 6	6 TO 9	9 TO 12
LESS THAN 50 KIPS	1	4	7	10
50 TO 80 KIPS	2	5	8	11
80 TO 100	3	6	9	12

Figure 15. Mission Type Classification for 120 Mission Types Expected to be Flown by the C-5A Transport (Continued)



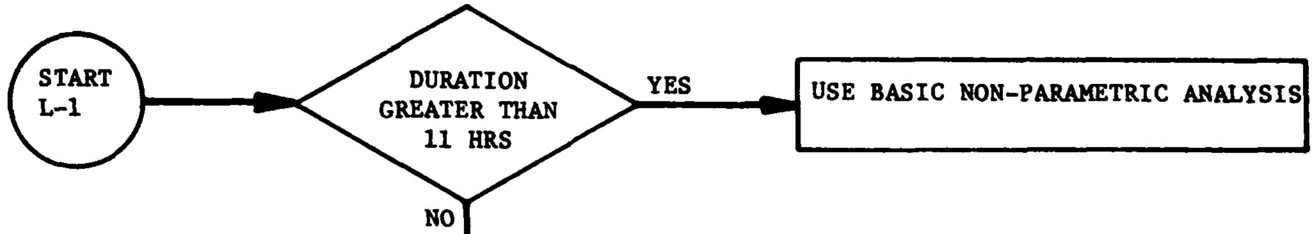
	LESS THAN 3	3 TO 6	6 TO 9	9 TO 12
	1	4	7	10
	2	5	8	11
	3	6	9	12

DURATION (HRS) / CARGO WEIGHT KIPS	LESS THAN 3	3 TO 6	6 TO 9	9 TO 12
LESS THAN 50	41	44	47	50
50 TO 80	42	45	58	51
80 TO 100	43	46	49	52

ion for 120 Mission Types Expected
Transport (Continued)

2

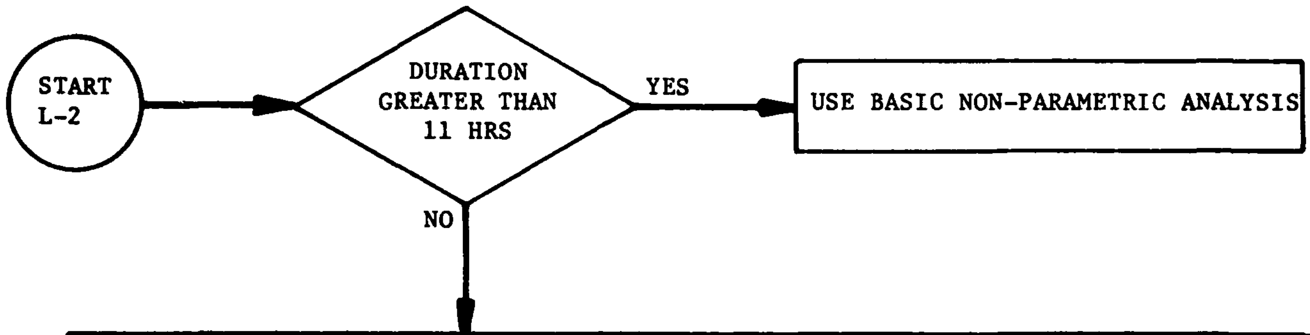
3



MISSION TYPE I.E. BY MISSION DURATION AND CARGO WEIGHT

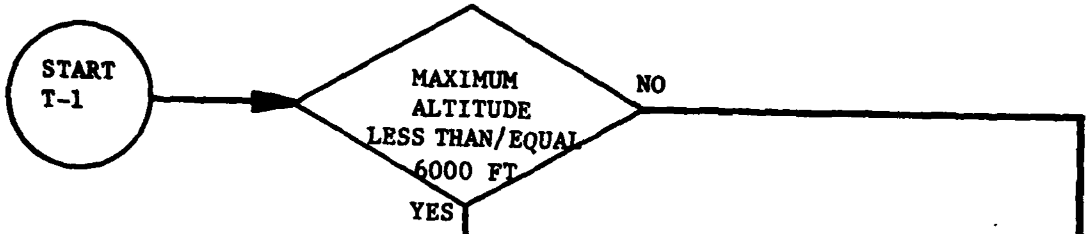
CARGO WEIGHT (KIPS) \ DURATION (HRS)	LESS THAN 3	3 TO 5	5 TO 7	7 TO 9	9 TO 11
100 TO 115	13	20	27	33	38
115 TO 130	14	21	28	34	39
130 TO 140	15	22	29	35	40
140 TO 150	16	23	30	36	NP
150 TO 157.5	17	24	31	37	NP
157.5 TO 165	18	25	32	NP	NP
165 TO 170	19	26	NP	NP	NP

Figure 15. Mission Type Classification Logic for 120 Mission Types Expected to be Flown by the C-5A Transport (Continued)



MISSION TYPE I.D. BY MISSION DURATION AND CARGO WEIGHT					
DURATION (HRS) / CARGO WEIGHT	LESS THAN 3	3 TO 5	5 TO 7	7 TO 9	9 TO 11
100 TO 115	53	60	67	73	78
115 TO 130	54	61	68	74	79
130 TO 140	55	62	69	75	80
140 TO 150	56	63	70	76	NP
150 TO 157.5	57	64	71	77	NP
157.5 TO 165	58	65	72	NP	NP
165 TO 170	59	66	NP	NP	NP

Figure 15. Mission Type Classification Logic for 120 Mission Types Expected to be Flown by the C-5A Transport (Continued)



NUMBER OF LANDINGS / DURATION (HRS)	LANDING FUEL WEIGHT LESS THAN 30 KIPS			LANDING FUEL WEIGHT GREATER THAN 30 KIPS		
	1 TO 6	7 TO 12	13 TO 17	1 TO 6	7 TO 12	13 TO 17
0 TO 2	85	89	NP	95	99	NP
2 TO 3	86	90	NP	96	100	NP
3 TO 4	87	91	93	97	101	103
4 TO 5	88	92	94	98	102	104

LANDING FUEL WEIGHT LESS THAN 30 KIPS			LANDING FUEL WEIGHT GREATER THAN 30 KIPS		
1 TO 6	7 TO 12	13 TO 17	1 TO 6	7 TO 12	13 TO 17
105	108	NP	113	116	NP
105	108	NP	113	116	NP
106	109	111	114	117	119
107	110	112	115	118	120

Figure 15. Mission Type Classification Logic for 120 Mission Types Expected to be Flown by the C-5A Transport (Concluded)

(2) Any training flight with a cargo greater than 50 KIPS, takeoff fuel greater than 174 KIPS, a duration greater than 5 hours or more than 17 landings

(3) Any logistic flight having a duration of more than 12 hours or a cargo weight greater than 170 KIPS, a fuel weight at landing greater than 125 KIPS, or a maximum altitude less than 25,000 feet under certain conditions.

Description of the C-5A IAT Parametric Analysis Method

For each structural location required to be tracked, all of the predefined mission types were subjected to a series of cycle-by-cycle crack growth analyses using a range of initial crack lengths and effective retardation parameters. The output was an array of interrelated parameters which are schematically described by the curves in Figure 16. Interpolation between parameters is done using a log-log method. To facilitate interpolation the crack length is related to the normalized stress intensity factor (SIF) α. This results in a set of relationships between the normalized SIF and the incremental crack growth per flight (da_i/dF_i). For a specific flight or number of flights, da_i/dF_i becomes Δa_i. The normalized SIF is

$$\alpha = \beta\sqrt{\pi a} \tag{27}$$

where

a = crack length

β = correction factor for local boundary conditions

The initial stress (σ_n) at the start of each flight is related to the plastic zone size (r_p) and the plastic zone correction factor (c) based on a Lockheed retardation concept.

$$\sigma_i = (r_{p(i-1)}/\alpha_i^2\ C)^{1/2} \tag{28}$$

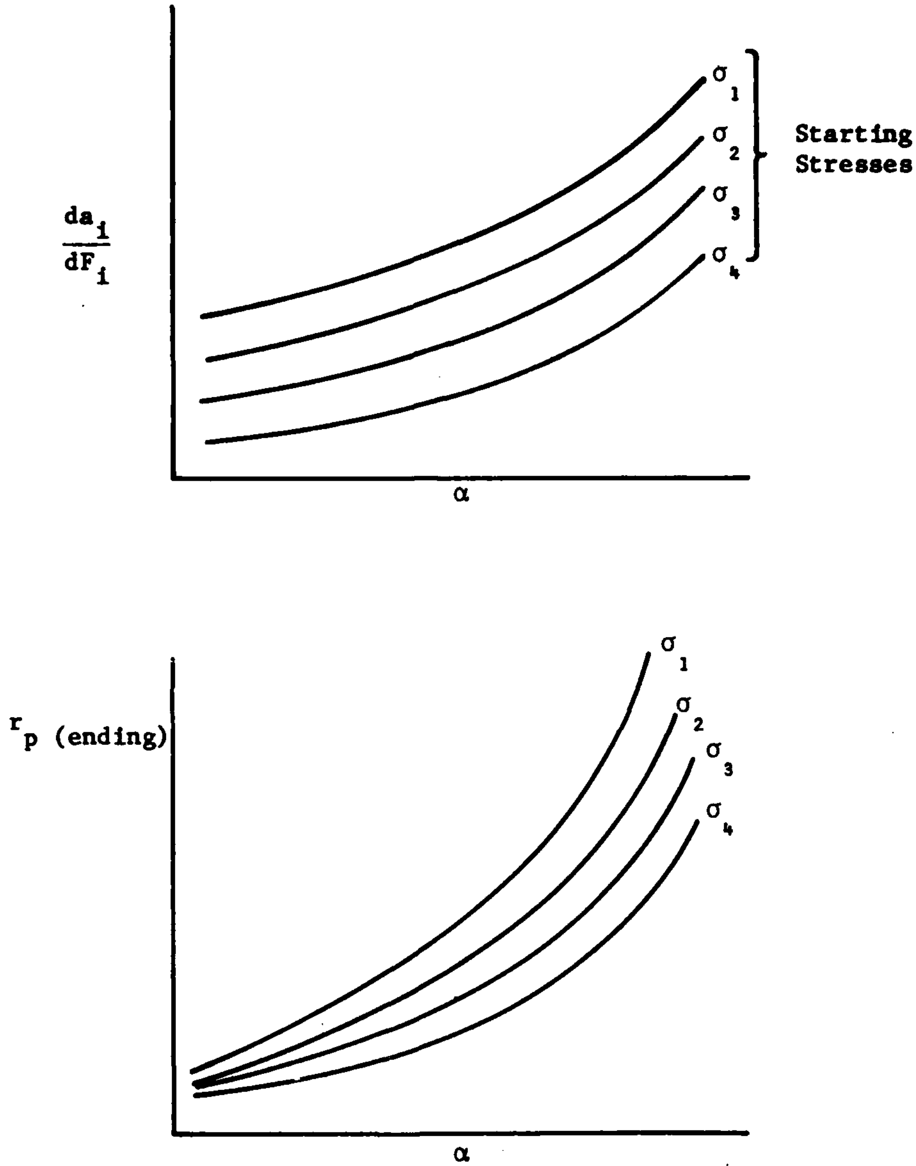


Figure 16. Normalized SIF (α) versus Crack Growth per Flight (da_i/dF_i) and the Plastic Zone Size (r_p)

Briefly, the parametric IAT method is as follows:

(1) Define the initial conditions (assuming that $a_1 = 0.050$ inches)

$$\alpha_1 = \beta\sqrt{\pi(0.050)} \tag{29}$$

$$\sigma = 0.0$$

(2) Identify the mission type which most closely matches Flight Number 1.

(3) Enter the parametric curves for $\alpha = \alpha_1$ and determine Δa_1

(4) Calculate the crack length (a) at the end of Flight Number 1 (which also is the crack length at the start of Flight Number 2).

$$\alpha_2 = \beta\sqrt{\pi(a_1 + \Delta a_1)} \tag{30}$$

(5) Enter the retardation parametric curves for $\alpha = \alpha_1$ and determine r_p

$$r_{p_1} = r_p \tag{31}$$

(6) Calculate the ending retarded stress state for Flight 1.

$$\sigma_2 = (r_{p_1}/\sigma_2^2\ C)^{1/2} \tag{32}$$

(7) Identify the mission type for the second flight and access the appropriate mission type parameters.

(8) Enter the parameter curve for $\alpha = \alpha_2$ and determine Δa_2.

(9) Calculate the new crack length parameter α_3

$$\alpha_3 = \beta\sqrt{\pi(a_1 + \Delta a_1 + \Delta a_2)} \tag{33}$$

(10) Determine the new value for r_p for $\alpha = \alpha_2$.

$$r_{p_2} = r_p \tag{34}$$

(11) Calculate the ending retarded stress for Flight 2.

$$\sigma_3 = (r_{p_2}/\sigma_3^2 C)^{1/2} \tag{35}$$

(12) Determine the largest stress magnitude for applied partial cycles as indicated by a partial cycle retardation accounting routine. (This routine cannot be described here because of its proprietary nature.) This value is then an alternate value for σ_3.

(13) Determine the larger of the two values of σ_3 as determined in steps 11 and 12. The larger σ_3 becomes the starting stress for the next flight.

(14) Repeat the above routine for each succeeding flight.

In terms of the IAT program, the significant outputs from the cumulative crack growth calculation routine for each structural control point are:

(1) A cumulative crack growth history

$$a_n = a_i + \sum_{j=1}^{n} \Delta a_j \qquad \text{for n flights or hours} \tag{36}$$

(2) A crack growth rate parameter (da/dt) based on the rate of crack growth starting from an arbitrary initial flaw (usualy 0.050 inches) and caused by the individual aircraft's current load spectrum applied for a finite time period, and

(3) A crack growth rate parameter defined as above except that the standard mission type load spectrum was used instead of the individual aircraft's load spectrum.

The first output parameter provides the raw crack growth data, from which parameters such as remaining life and time to inspection can be calculated. The second and third parameters (crack growth rates) provide data by which the severity of current flying can be compared to the programmed or predicted severity.

Output Data from the IAT Program

Types of Data

The output data developed by the IAT system can be divided into several types of data. The major types are (1) data developed by the crack growth prediction routine for specific structural control points on a specific aircraft, (2) data describing the usage of the aircraft which was developed from the flight usage log form, and (3) aircraft, unit, and base identification data. Table 6 outlines the detailed aspects of the IAT output data.

With the limits of the input data flight log form, there is no way to identify relative severity of particular mission types. This lack of severity data may affect the crack growth calculations over the long run if there is a change in the basic mission of the force. The current methodology accounts for flight load environment severity variations by using large amounts of L/ESS data describing the current mission mix and mission profiles and arriving at an average long term load severity effect. This approach is effective just so long as there are no significant changes in the L/ESS data pertaining to part or all of the force. In fact if any group of aircraft within the force consistently experiences a load environment which is significantly different than the average load spectra then that group will be analyzed using an unrealistic load history. The effect may be conservative or unconservative, depending on the specific case studied.

Individual Aircraft Tracking and Force Management Data

The C-5A IAT and Force Management programs are very extensive and the amount and variety of individual aircraft and force management data available is quite large. The overall C-5A IAT and FM data system is described in great detail in the University of Dayton Reports on a generalized IAT data system [Reference 25 and 26]. This section will summarize those reports.

For purposes of this report, it is useful to define an arbitrary boundry line between the IAT program and the FM program. The implications of paragraphs 5.4.5 and 5.4.2 of MIL-STD-1530A limit the IAT program to the generation and analysis of analytic crack growth predictions for structural control points

on the individual aircraft, and the generation and analysis of associated usage data which can be used to implement and/or revise the Force Structural Management Plan. Therefore, in our view, the types of data listed in Table 6 are IAT output parameters which in effect are inputs to the Force Management Program.

Obviously, the IAT output parameters can be manipulated in a variety of ways to provide usage data, maintenance action data, and operational planning data - both for the individual aircraft and for the entire force (or subgroups of the force) in terms of population statistical trends. However, only those data which are strictly usage data, that is, actual IAT output parameters (Table 6) or data directly processed from the IAT output parameters (manipulated forms of the IAT output data), should be considered as IAT data. Thus the major data categories shown in Figure 17 are considered to combine both IAT and FM data items. Most of the data items in the first three categories are IAT data, while categories 4 and 5 are strictly force management data items generated only in part from IAT output (usage) parameters. The above referenced University of Dayton reports consider all of the data catagories (Figure 17) to be IAT system data. However, it is reasonable to consider that almost all of the maintenance action data should be considered strictly FM data. The disagreement is to some degree a matter of semantics and is complicated by the fact that a single overall software system (see Table 7) made up of independent modules and submodules is used to generate the IAT output usage data, present various manipulated versions of the IAT output usage data, and generate an extensive array of FM (maintenance action) data. This software system is called the Generalized Individual Aircraft Tracking (GIAT) Software System and was developed by the University of Dayton [25] for SA-ALC. All of the computer program modules are written in COBOL except for the graphic routines and the Lockheed generated program modules for the crack growth calculations which are written in FORTRAN. The major program modules and functions are shown in Table 7.

Because of the thoroughness of the C-5A IAT/FM data management program, it can serve as an example for other IAT programs. For this reason a description of the data program has been included in the report as Appendex A.

TABLE 6. SUMMARY OF IAT OUTPUT DATA

TYPE OF OUTPUT DATA	DESCRIPTION
Identification Data	Aircraft Serial Number (USAF/Manfacturer)
	Aircraft Unit (Squadron, Group, Wing, Command)
	Aircraft Home Base
Crack Growth Data (For Each Structural Control Point)	Initial Crack Size Incremental Crack Growth Per Flight Cumulative Crack Size
	Actual Usage and Predicted Crack Growth Rate Parameter (da/dt)
Usage Data (For Each Flight)	Flight Time and Processed Flight Time
	Flight Sequence Number and Date
	Mission Type I.D. (or Non-Standard Type Mission)
	Landing Events (Final, Stop and Go, Touch and Go)
	Fuselage Pressure Cycles
	Special Events: Cargo Airdrops Aerial Refueling Cargo Jettison Fuel Jettison Contour Flying Substandard Runway Landing
	Mission Profile Descriptors:
	Cruise: Duration, Altitude, Airspeed — Landings: Time; Take-off: Time — Weights: Take-off Gross, Fuel, Cargo
	Special Events: Start/Stop Times Incremental Weight Altitude Route Code, Mode, Airspeed — Terrain Following

1. <u>Summary Data and Statistics</u>

2. <u>Individual/Force Damage Tolerance Status</u>

   Crack Growth History
   Crack Growth Rate Summaries
   Remaining Crack Growth Life Capacity
   Service Life Capacity

3. <u>Past Usage Characterization Statistics</u>

   Mission Parameter Usage
   Mission Type Mix Usage
   Special Events Usage

4. <u>Maintenance Actions and Schedules</u>

   Near/Far Term Schedules
   Manpower Requirements
   Action Items
   Inspection/Maintenance Status

5. <u>Utilities Data</u>

   Identification Data
   Effectiveness Data

Figure 17. Major IAT and Force Management Data Item Classes

TABLE 7. GENERALIZED IAT MODULE FUNCTIONS AS DEVELOPED BY THE UNIVERSITY OF DAYTON AND LOCKHEED-GEORGIA COMPANY

MODULE	MODULE NAME	PRINCIPAL FUNCTIONS
I	EDIT	o VERIFY FIELD INPUT DATA o SORT AND MERGE DATA CHRONOLOGICALLY o CHARACTERIZE MISSIONS (USAGE)
II	CALCULATE	o FILL IN MISSING DATA o INCREMENT CRACKS, DETERMINE RATE o DETERMINE LIFE USED AND REMAINING o RECORD USAGE STATICS
III	FILE/UPDATE	o STORE AIRCRAFT DATA o STORE USAGE DATA o STORE MAINTENANCE DATA o STORE DAMAGE DATA
IV	REPORT	o DEFINE USAGE ACTIVITY o DEFINE CHANGE IN FORCE STATUS o DEFINE MAINTENANCE SCHEDULE

Note: 1. Table is from Page 3 of Reference 25.

Discussion of Crack Growth Data Manipulation

Because of the nature and scope of the C-5A IAT program and its significance as a typical large aircraft program, a brief description of the C-5A IAT program crack growth data and their use is presented here.

As part of the damage tolerance analysis (DTA), each structural control point has a crack growth curve which was generated on the basis of anticipated mission mix usage over the planned life of the aircraft. A typical case is shown in Figure 18 (b), which plots the crack length (growth) as a function of hours of baseline mission mix usage. The crack length at the damage limit can be defined in several ways:

(1) The critical crack length at which unstable crack growth will occur, or

(2) The crack length which defines the limit at which some maintenance action will be taken (for example, removal of damage by reaming a fastener hole).

In the case of the C-5A, the damage limit is assumed to be the critical crack length (a_f). In Figure 18b, the crack growth calculated for an individual aircraft based on that aircraft's usage (as reported in the usage flight logs) is shown as $a_{A/C}$ - the current predicted length at the time $t_{A/C}$. However, the crack length $a_{A/C}$, when projected onto the baseline curve, is found to be equivalent to a crack length at a different time (t_{MU}) for the baseline usage. The remaining life is then calculated without the use of a scatter factor:

$$t_L = t^*_{MU} - t_{MU} \tag{37}$$

Since the USAF specifies the future monthly usage rate (U_p) for a number of years, the predicted remaining life (calender time) to critical crack leugth is

$$L = t_L/U_p \tag{38}$$

The predicted calender date at the time of failure (damage limit) is calculated by adding the predicted remaining life to the current date:

$$D_p = D_c + L \tag{39}$$

where D_c = current date

L = predicted remaining life in convenient time units.

The predicted calendar date for the damage limit can be used in several ways to establish periodic base and depot maintenance actions. In general the major considerations are (1) inspectability of the control point, (2) repairability (technically and economically) of the control point structure, (3) impact on the operational readiness, and (4) the schedule for other base/depot maintenance actions.

Inspection intervals are based on either the assumed initial manufacturing crack size or the anticipated missed crack size as a result of the most recent inspection. The initial inspection for the C-5A is (ideally) at $1/2(t^*_{MU})$ with subsequent inspections depending on the time between the inspection time and the service limit time (See Figure 19). In general, the inspection interval is:

$$t_{Int} = 1/2\ (t^*_{MU} - t_d) \tag{40}$$

where

t_d = the time expended for a crack length a_d which is the largest crack length that can be missed during the inspection.

For the case of subsequent inspections, the time t_d becomes t_{PI} and the next inspection (t_{NI}) is scheduled for

$$t_{NI} = t_{Int} = 1/2\ (t^*_{MU} - t_d) \tag{41}$$

The calendar date will be

$$D_{NI} = D_C + (t_{NI} - t_{MU})/U_p \tag{42}$$

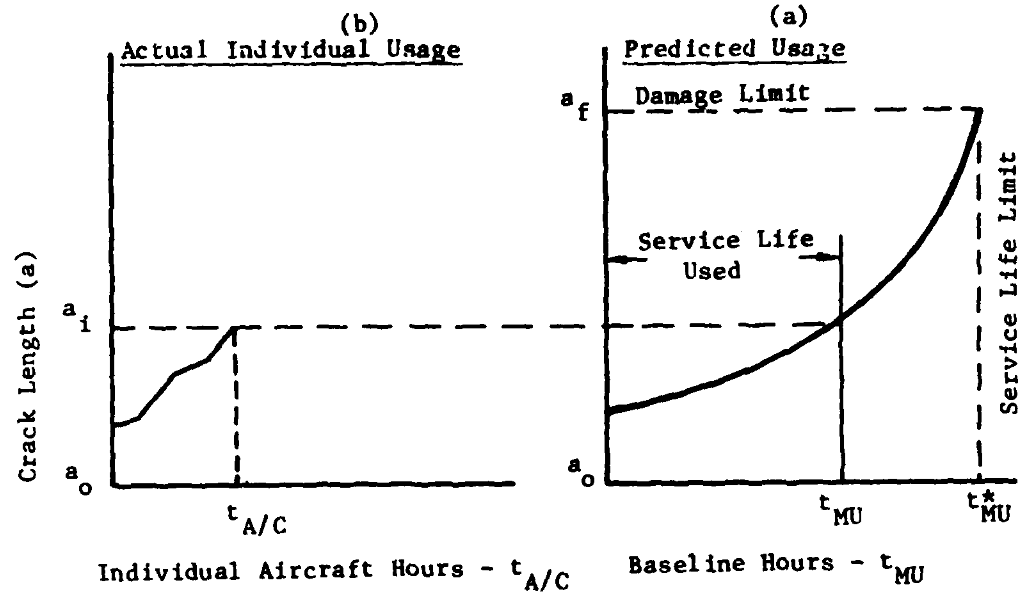


Figure 18. Comparison of Individual Aircraft Crack Growth to FSM Planned Crack Growth for a Specified Control Point

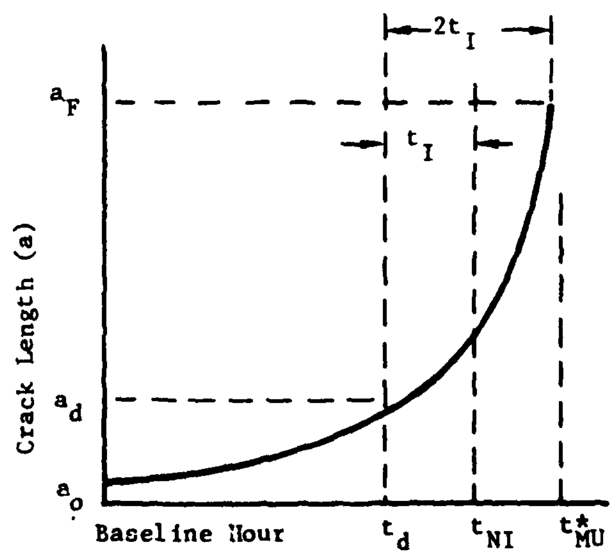


Figure 19. Determining the Inspection Interval Using the FSM Baseline Curve

Data are not available on the nature and timing of the C-5A inspections. However, it is evident that the force manager may develop one of several concepts for determining the inspection period.

The concept of resetting the current crack length on the basis of inspection is used on several aircraft types. However, the C-5A IAT program continues to track both cracks, that is, the predicted crack growing from the initial assumed manufacturing flaw size (a_1) and the crack length assumed due to inspection (a_2). Depending on the actual behavior of the airframe structure, the crack growth of the second crack may be ahead or behind that of the initial first crack. The time to the next inspection can be calculated for both cracks and the more conservative time used for the actual subsequent inspection. The program cost for tracking two cracks for each structural control point is negligible but the additional information can be valuable to the force manager.

Case Study: Lockheed C-141A Transport

Background

The IAT program for the C-141 transport is in the process of being modified from a parametric cumulative fatigue damage (Miner/Palmgren) method to a parametric crack growth method. The description, comments, and recommendations which follow are based on the proposed IAT program described in Reference 27.

The C-141A IAT Program is a parametric type of program using a manually completed flight log titled "C-141 Aircraft Usage Log" to define the flight "data blocks" which the aircraft experienced in each reported flight. A typical form is reproduced as Figure 20. As can be noted, there are only six types of mission flight segments or blocks: climb, cruise, descent, contour flying, extended traffic, and inflight refueling and (in the nonflight category) several ground blocks. This usage log was originally designed to be used in a "data block" usage type of parametric program [4].

A data block is defined as an identifiable type of flying over an easily measurable period of time which is sufficiently consistent in terms of flight characteristics and air loads imposed on the aircraft. This uniformity of

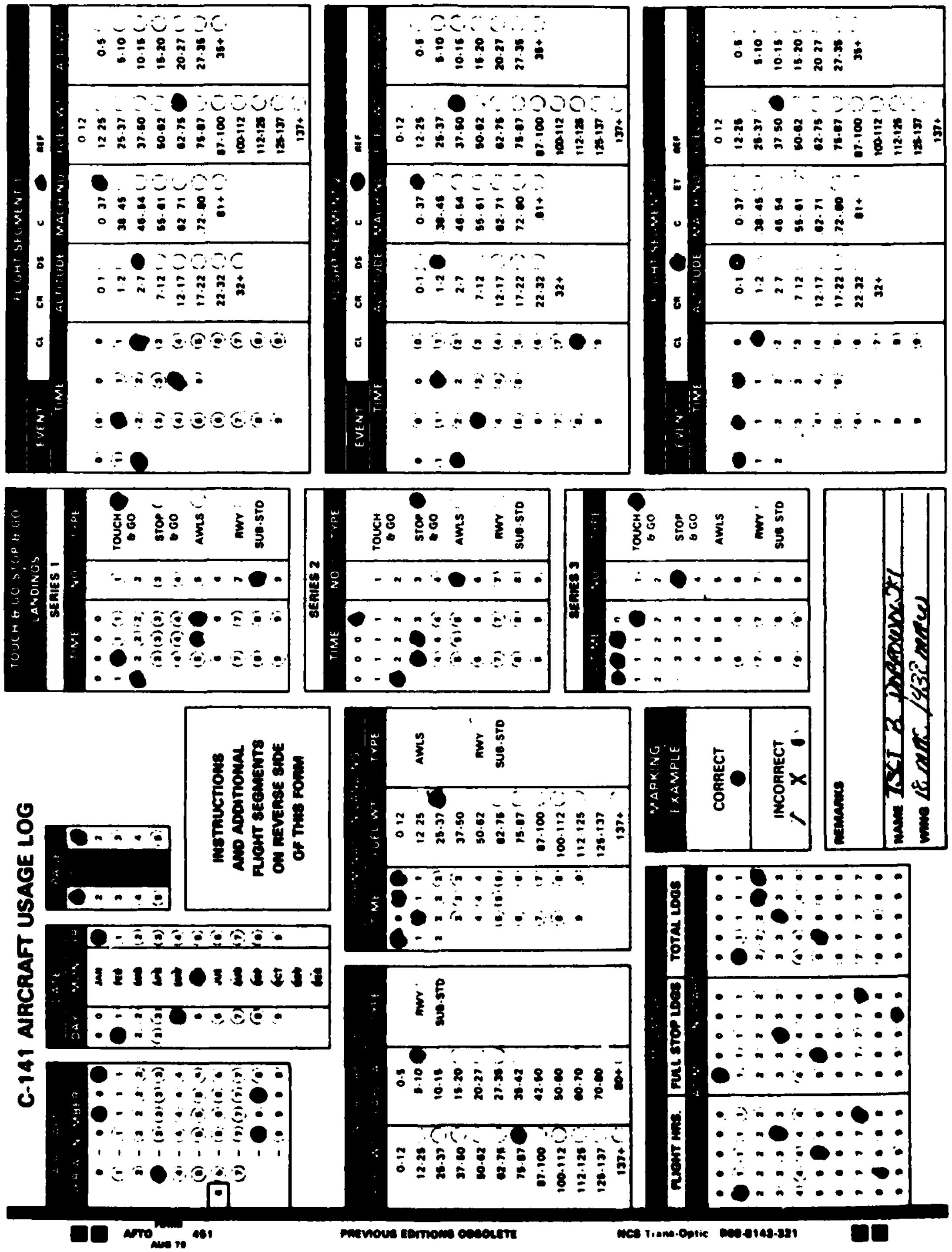


Figure 20. Sample Flight/Usage Log for C-141 Transports

FLIGHT SEGMENT 4

EVENT TIME				ALTITUDE	MACH NO	FUEL WT	A.D. WT
	CL	CR	DS	C	ET	REF	
						0-12	
0	0	0	0	0-1	0-37	12-25	0-5
1	1	1	1	1-2	38-45	25-37	5-10
2	2	2	2	2-7	46-54	37-50	10-15
	3	3	3	7-12	55-61	50-62	15-20
	4	4	4	12-17	62-71	62-75	20-27
	5	5	5	17-22	72-80	75-87	27-35
	6		6	22-32	81+	87-100	35+
	7		7	32+		100-112	
	8		8			112-125	
	9		9			125-137	
						137+	

EVENT TIME				ALTITUDE	MACH NO	FUEL WT	A.D. WT
	CL	CR	DS	C	ET	REF	
						0-12	
0	0	0	0	0-1	0-37	12-25	0-5
1	1	1	1	1-2	38-45	25-37	5-10
2	2	2	2	2-7	46-54	37-50	10-15
	3	3	3	7-12	55-61	50-62	15-20
	4	4	4	12-17	62-71	62-75	20-27
	5	5	5	17-22	72-80	75-87	27-35
	6		6	22-32	81+	87-100	35+
	7		7	32+		100-112	
	8		8			112-125	
	9		9			125-137	
						137+	

EVENT TIME				ALTITUDE	MACH NO	FUEL WT	A.D. WT
	CL	CR	DS	C	ET	REF	
						0-12	
0	0	0	0	0-1	0-37	12-25	0-5
1	1	1	1	1-2	38-45	25-37	5-10
2	2	2	2	2-7	46-54	37-50	10-15
	3	3	3	7-12	55-61	50-62	15-20
	4	4	4	12-17	62-71	62-75	20-27
	5	5	5	17-22	72-80	75-87	27-35
	6		6	22-32	81+	87-100	35+
	7		7	32+		100-112	
	8		8			112-125	
	9		9			125-137	
						137+	

INSTRUCTIONS

Use No. 2 or softer pencil. Do not use ballpoint or fiber-tip pens.

Darken response positions completely. Do not fold or punch holes. Do not make stray marks outside of the REMARKS section.

All time entries use the ZULU time at the beginning of the event. All weights are in thousands of pounds. All altitudes are in thousands of feet.

Complete entries with the information shown below.

1. AIRCRAFT SERIAL NUMBER: Second digit of the year group plus the last four digits of the serial number. The first digit of the year group is pre-printed and need not be marked.

2. DATE: Day, month and last digit of the year of the flight.

3. PAGE: Page number and total number of pages in this flight. Single-page flights are marked "1 of 1". Multi-page flights are numbered sequentially, such as "1 of 3", "2 of 3", and "3 of 3".

4. INITIAL TAKEOFF: Mark the appropriate weight bands for the total fuel weight and the total payload weight. If the runway or taxiway was other than surfaced and smooth, mark RWY SUB-STD.

5. TERMINATION LANDING: Mark the time at the end of the landing and the total landing fuel weight. If the touchdown was under the control of the All Weather Landing System, mark AWLS. Mark RWY SUB-STD if appropriate.

6. CUMULATIVE DATA: Record the total airframe hours to the nearest hour and the cumulative full-stop and total landings at the start of the flight.

7. TOUGH & GO/STOP & GO LANDINGS: If flown, record the time the series of landings began and the total number of landings made. Identify the type as either TOUCH & GO or STOP & GO. Mark AWLS or RWY SUB-STD if appropriate.

8. FLIGHT SEGMENTS: These blocks may record six different types of flight segments. As defined in T.O. 1C-141A-102, they are:

CL - Climb	C - Contour Flying
CR - Cruise	ET - Extended Traffic
DS - Descent	REF - Inflight Refueling

All segment types require time, altitude, and fuel weight entries. Additionally, a Mach number entry is required for a cruise, an extended traffic, or an inflight refueling. If an airdrop occurs, mark the appropriate airdrop weight range for that cruise segment.

An inflight refueling event may follow a climb, a descent, or a cruise. The event is considered to have begun when the pilot begins making extensive control inputs to position the aircraft behind the tanker.

Mail completed forms to: WR-ALC/MMSRDB
Robins AFB GA 31098

Figure 20. Sample Flight/Usage Log for C-141 Transports (Concluded)

flight characteristics and air load history is the basis for concluding that the fatigue damage rate will be consistent over a long period of usage for the particular data block. Short term variations in flight parameters and the resulting variations in fatigue damage will occur, but over a long period of time, the "data block" will maintain its parametric population averages. Typically, a data block is similar to a mission segment except that it is further characterized (in the case of the C-141) by altitude, Mach number, fuel weight, and cargo air-drop weight. It is obvious that a large number of data blocks must be defined to cover the full range of flight usage. The original C-141 fatigue tracking program used 3,204 data blocks to represent all ground and flight usage. The proportion of ground to flight data blocks is not known. However, it is interesting to note that if all of the cargo and fuel weight categories specified on the usage log were to be used in the parametric analysis, the required number of data blocks would quadruple (to 12,816).

Fracture Tracking Program

In the process of converting from the original fatigue tracking program to a crack growth tracking program, Lockheed-Georgia Company reconsidered the method of defining the IAT input parameters. Two methods were studied - the original data block method and a "mission assignment" method which is referred to as the mission type method in this report.

In the Lockheed evaluation, the following factors were considered:

a) Analytic sensitivity to the parameter range defined by a data block can be significant. For example, the crack growth rate at Mach 0.72 could be significantly less than the crack growth rate at Mach 0.80. Yet both of the airspeed parameters define one airspeed block (see Figure 20)

b) Load interaction effects on crack growth (retardation) which could be applied within the data blocks (intrablock) and between data blocks (interblock) can be significant

c) Load interaction effects on crack growth due to the sequential order of loads within the data blocks and the sequencing of the data blocks within a flight may result in variations in crack growth

d) Data storage and processing expense can vary significantly depending on the complexity of the IAT program.

In considering the range of sensitivity of the crack growth analysis versus the size of the data blocks, it was concluded that finer subdivisions were desirable. This consideration led to an estimate of 10,000 or more data blocks [Reference 28, Page 6.5], as compared to the 3,204 currently used.

To account for intraflight load interaction (crack retardation) between data blocks, the number of required preceding and trailing identifiers for each data block greatly complicated the IAT crack growth analysis computer program. Interflight load interaction was determined to be negligible. However, the intrablock retardation was considered to be necessary for the parametric analysis. It was concluded that either the data block method or the mission type method could be designed to be equally accurate [Reference 27, Page 6.8]. The data block usage method has several advantages. First, a large but practical number of data blocks can accurately describe the crack damage. Second, the linking of a number of data blocks in sequence will account for interblock load interaction effects and load sequence effects. The disadvantages are the need for defining a large number of data blocks and, depending on the degree of complexity desired, the large amount of computer time needed to compute the crack growth.

Since the C-141 transport flies a limited number of routine and predictable missions, basing the parametric analysis on a set of mission types was recommended by the contractor. A preliminary review indicated that a set of 45 separate types of missions is adequate. Further evaluation may indicate that more mission types are necessary or that an interpolating scheme is needed. It is interesting to note that prior to 1969 the anticipated number of mission types was 13.

Another problem common to both approaches is the so-called flight severity problem. It must be recognized that the aircraft will randomly experience flight load conditions of varying severity - primarily due to varying gust load severity. Consequently, four representative levels of flight severity were defined and used in the analysis.

This quadruples the 45 basic mission types needed to directly account for the severity of flight. However, it is obvious that the usage log form cannot be used to provide quantitative data relative to flight severit--.

In summary, Lockheed-Georgia selected the mission type input parameter approach because: (1) it will be as accurate as the data block approach, (2) it will permit incorporation of flight severity effects at a lower level of complexity, (3) it categorizes data in a mission format which is more meaningful and useful to USAF users, and finally (4) it will enable the IAT program to run at substantially lower computer costs.

IAT Input Parameters

Mission Type Description

As outlined in Reference 27, the recommended C-141 IAT program uses 45 basic mission type profiles. These mission type profiles are made up of specific misison segment types which correspond roughly to the old blocks. Each segment occurs in its natural or usual sequence and is defined by additional parameters such as gross weight, cumulative fuel burnoff, altitude, airspeed, elapsed time, and aircraft configuration. A typical example is shown in Table 8. The mission type stress spectrum is built up by segments. For certain tracking control points, the local shear and axial stresses are combined in different ratios for different segment types.

The usage log which is completed by a flight crew member is used as the only input data source for a computer program which scans the input data and determines which of the predescribed mission types most closely fits the actual flight. A typical decision tree diagram for determining whether one of the ten different training mission types has occurred is shown in Figure 21. The logic scheme shows that only three event parameters and one flight parameter are required to identify the mission (in this example) as Fracture Tracking Profile 32. These data items are: the occurrence or non-occurrence of a cargo-airdrop, touch-and-go landing(s) (TAG), and stop-and-go (SAG) landing(s), and the cargo weight. Using the Lockheed-Georgia Co. decision trees diagrams, all 45 mission types were analyzed and the minimum numbers of parameters, for

TABLE 8. C-141A MISSION PROFILE NO. FTP-32
TYPE: TRAINING

SEG. NO.	SEGMENT EVENT	VALUES AT END OF SEGMENT						
		GROSS WT.	CUM. FUEL BURNOFF	ALTITUDE (FT.)	AIRSPEED (KEAS)	ELASPED TIME (MIN.)	SEG. TIME (MIN.)	CONFIG. CODE
1	RAMP	21600		S.L.				
2	TAXI	214600	1400	S.L.		8	8	2
3	TAKE-OFF ROLLOUT	214100	1900	S.L.		9	1	2,3
4	T. O. AND ACCELERATE TO CLIMB SPEED	213000	3000	1500	170	10	1	1
5	LOW ALTITUDE CRUISE	212100	3900	1500	.374/240	14	4	1
6	ENROUTE CLIMB	211600	4400	2000	180	16	2	1
7	TRAFFIC	211100	4900	2000	136	18	2	2,3
8	TAG LANDING APPROACH	210900	5100	S.L.	111	19	1	2,4
9	TOUCH AND GO LANDING AND ROLLOUT	210600	5400	S.L.		20	1	2,4
10	TAG CLIMB	210100	5900	2000	150	22	2	2,3
11	TRAFFIC	208000	8000	2000	136	32	10	2,3
12	TAG LANDING APPROACH	207800	8200	S.L.	111	33	1	2,4
13	TAG LANDING AND ROLLOUT	207600	8400	S.L.		34	1	2,4
14	TAG CLIMB	207100	8900	2000	150	36	2	2,3
15	TRAFFIC	205000	11000	2000	136	46	10	2,3
16	TAG LANDING APPROACH	205800	11200	S.L	111	47	1	2,4
17	TAG LANDING AND ROLLOUT	204600	11400	S.L.		48	1	2,4
18	TAG CLIMG	204100	11900	2000	150	50	2	2,3
19	TRAFFIC	202000	14000	2000	136	60	10	2,3
20	TAG LANDING APPROACH	201800	14200	S.L.	111	61	1	2,4
21	TAG LANDING AND ROLLOUT	201600	14400	S.L.		62	1	2,4
22	TAG CLIMB	201100	14900	S.L.	150	64	2	2,3

Note: 1. Configuration Codes: Clean (1)
Gear Down (2)
T/O Flaps (3)
Landing Flaps (4)
Spoilers Deployed Ground (5)

TABLE 8. C-141 MISSION PROFILE NO. FTP-32 (continued)
TYPE: TRAINING

SEG. NO.	SEGMENT EVENT	VALUES AT END OF SEGMENT						
		GROSS WT.	CUM. FUEL BURNOFF	ALTITUDE (FT.)	AIRSPEED (KEAS)	ELASPED TIME (MIN.)	SEG. TIME (MIN.)	CONFIG. CODE
23	TRAFFIC	199000	17000	2000	136	74	10	2,3
24	TAG LANDING APPROACH	198000	17200	S.L.	111	75	1	2,4
25	TAG LANDING AND ROLL OUT	198600	17500	S.L		76	1	2,4
26	SAG CLIMG	198400	17600	2000	150	77	1	2,3
27	TRAFFIC	196400	19600	2000	136	87	10	2,3
28	SAG LANDING APPROACH	196200	19800	S.L.	111	88	1	2,4
29	SAG LANDING AND ROLLOUT	196200	19800	S.L.		89	1	2,4,5
30	TAXI	195500	20500	S.L.		92	3	2
31	T.O. ROLLOUT	193000	21000	S.L.		93		2,3
32	SAG CLIMG	194800	21200	2000	150	94	1	2,3
33	TRAFFIC	192800	23200	2000	136	104	10	2,3
34	SAG LANDING APPROACH	192600	23400	S.L.	111	105	1	2,4
35	SAG LANDING AND ROLLOUT	192600	23400	S.L.		106	1	2,4,5
36	TAXI	191900	24100	S.L.		109	3	2
37	T. O. ROLLOUT	19400	24600	S.L.		110	1	2,3
38	SAG CLIMB	191200	24000	2000	150	111	1	2,3
39	TRAFFIC	189200	26800	2000	136	121	10	2,3
40	SAG LANDING APPROACH	189000	27000	S.L.	111	122	1	2,4
41	SAG LANDING AND ROLLOUT	189000	27000	S.L.		123	1	2,4,5
42	TAXI	188300	27700	S.L.		126	3	2
43	T.O. ROLLOUT	189800	28200	S.L.		127	1	2,3
44	T.O. AND ACCELERATE TO CLIMB SPEED	186700	29300	2000	180	127	1	1

Note: 2. TAG means Touch and Go (landing)
3. SAG means Stop and Go (landing)
4. This table is from Ref.27 pages 6.73 to 6.75
5. This is a training mission

TABLE 8. C-141A MISSION PROFILE NO. FTP-32 (Concluded)
TYPE: TRAINING

SEG. NO.	SEGMENT EVENT	VALUES AT END OF SEGMENT GROSS WT.	CUM. FUEL BURNOFF	ALTITUDE (FT.)	AIRSPEED (KEAS)	ELASPED TIME (MIN.)	SEG. TIME (MIN.)	CONFIG. CODE
45	ENROUTE CLIMB	186200	29800	5000	250	129	3	1
46	CRUISE	183200	30800	5000	.370/223	134	5	1
47	ENROUTE CLIMB	184800	81200	1000	263	136	2	1
48	ENROUTE CLIMB	184200	31800	22000	272	140	4	1
49	HIGH ALTITUDE CRUISE	182200	33800	22000	.640/275	156	16	1
50	ENROUTE DESCENT	181700	34300	10000	260	163	7	1
51	ENROUTE DESCENT	181800	34800	2000	150	168	5	1
52	TRAFFIC	181000	35000	2000	127	170	2	2,3
53	FINAL LANDING APPROACH	180600	35400	S.L.	111	171	1	2,4
54	LANDING TOUCH DOWN	180600	35400	S.L.	102	171	0	2,4
55	LANDING ROLLOUT	180600	35400	S.L.		172	1	2,4,5
56	TAXI	179700	36300	S.L.		179	7	2

Note: 5. For this Mission: Ramp fuel = 78700 lbs, Ramp Cargo = 4811 lbs, Landing fuel = 42400 lbs, and average duration - 2 hrs, 38 min.

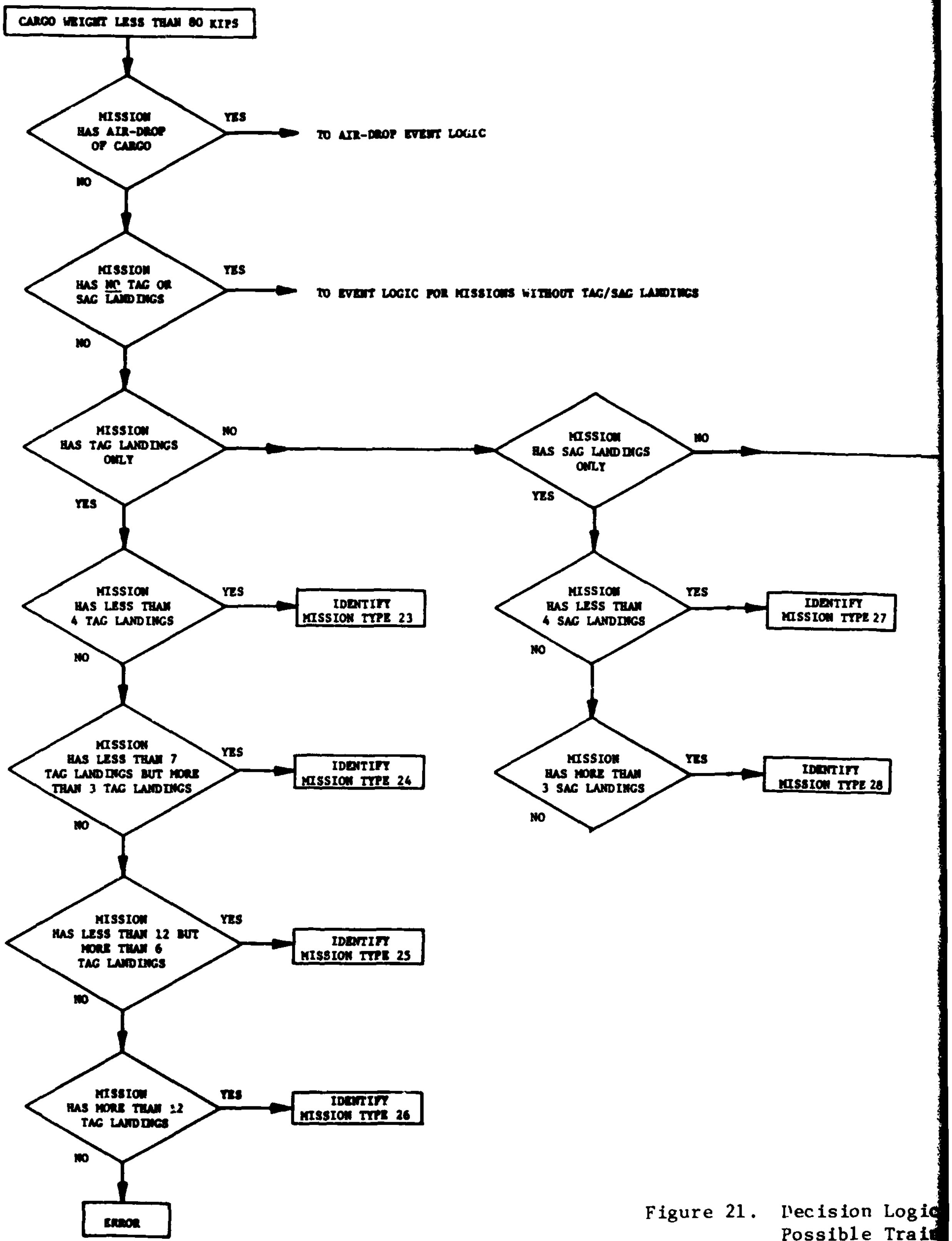
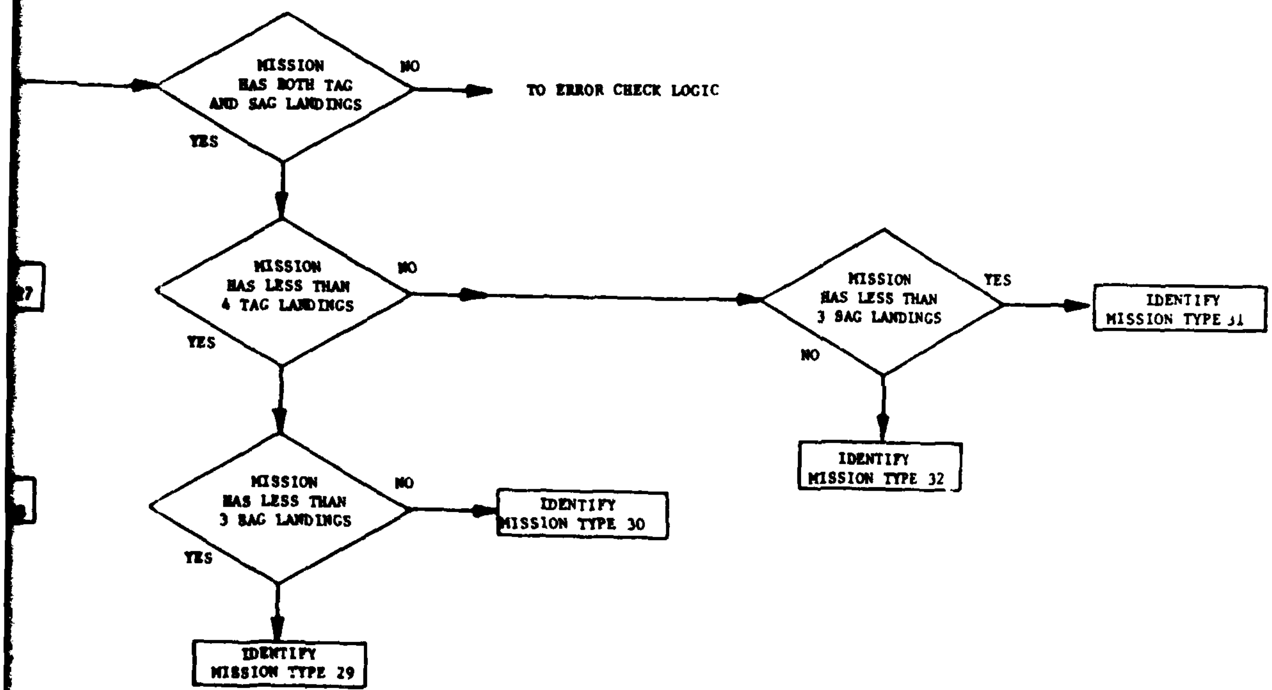


Figure 21. Decision Logic
Possible Trai



Logic Tree Diagram for Classification of Ten Training Missions for the C-141 IAT Program

TABLE 9. CONCEPTUAL IAT MICROPROCESSOR INPUT PARAMETER ARRAY FOR LARGE AIRCRAFT CLASS USING A PARAMETRIC TYPE CRACK GROWTH PROGRAM

LOGICAL EVENTS/ ACTIVITIES	CRUISE AT SELECTED ALTITUDE BANDS AND DURATION	DURATION OF MISSION	CARGO WEIGHT	FUEL WEIGHT	MACH NUMBER
INPUT PARAMETERS REQUIRED TO DETERMINE LOGICAL EVENT/ACTIVITY	ALTITUDE AIRSPEED NORMAL VERTICAL ACCELERATION (N_z)	TIME SIGNAL ENGINE START/STOP WEIGHT ON LANDING GEAR SIGNAL	DATA KEY BOARD INPUT	DATA KEY BOARD INPUT TOTAL FUEL FLOW	MACH NUMBER
SENSORS, TRANSDUCERS, AND INSTRUMENTATION REQUIRED TO SENSE, MEASURE OR RECORD INPUT PARAMETERS	ALTIMETER	ALTIMETER			
	AIRSPEED INSTRUMENTATION				AIRSPEED INSTRUMENTATION
		ELECTRO-MECHANICAL POSITION SENSOR (2 REQUIRED)			
	LINEAR VERTICAL ACCELROMETER				
	RATE OF CLIMB INSTRUMENTATION				
	MICROPROCESSOR CLOCK	MICROPROCESSOR CLOCK			
			DIGITAL ALPHA-NUMERIC KEYBOARD	DIGITAL ALPHA-NUMERIC KEYBOARD	
				FUEL FLOW TRANSDUCER	

TABLE 9. CONCEPTUAL IAT MICROPROCESSOR INPUT PARAMETER ARRAY FOR LARGE AIRCRAFT CLASS USING A PARAMETRIC TYPE CRACK GROWTH PROGRAM (CONCLUDED)

LOGICAL EVENTS/ ACTIVITIES	AIRDROP OF CARGO	TOUCH-AND-GO LANDING	STOP-AND-GO LANDING	CONTOUR FLYING AND DURATION
INPUT PARAMETERS REQUIRED TO DETERMINE LOGICAL EVENT	ALTITUDE AIRSPEED CARGO DOOR OPEN/CLOSE SIGNAL DATA KEY BOARD INPUT	WEIGHT ON LANDING GEAR SIGNAL AIRSPEED RATE OF CLIMB/ DESCENT ENGINE START/ STOP SIGNAL ENGINE POWER SIGNAL	WEIGHT ON LANDING GEAR SIGNAL AIRSPEED RATE OF CLIMB/ DESCENT ENGINE START/ STOP SIGNAL ENGINE POWER SIGNAL THRUST REVERSE SIGNAL BRAKE APPLICATION SIGNAL TIME SIGNAL	ALTITUDE AIRSPEED NORMAL VERTICAL ACCELERATION (N_z) TIME SIGNAL
SENSORS, TRANSDUCERS, AND INSTRUMENTATION REQUIRED TO SENSE, MEASURE OR RECORD INPUT PARAMETERS	ALTIMETER			ALTIMETER
	AIRSPEED INSTRUMENTATION	AIRSPEED INSTRUMENTATION	AIRSPEED INSTRUMENTATION	AIRSPEED INSTRUMENTATION
	ELECTRO-MECHANICAL POSITION SENSOR	ELECTRO-MECHANICAL POSITION SENSOR	ELECTRO-MECHANICAL POSITION SENSOR (3 REQUIRED)	
		ENGINE POWER INSTRUMENTATION	ENGINE POWER INSTRUMENTATION	LINEAR VERTICAL ACCELEROMETER
		RATE OF CLIMB INSTRUMENTATION	RATE OF CLIMB INSTRUMENTATION	
			MICROPROCESSOR CLOCK	
	DIGITAL ALPHA-NUMERIC KEYBOARD			

all mission types, were mapped (Table 9). The descriptive or defining parameters may be divided into three categories; event parameters (which indicated that an event occurred and in some cases its duration), response parameters (which consist of aerodynamic and inertial parameters), and aircraft configuration parameters (which describe the geometric configuration of the aircraft). The aircraft configuration parameters are not used in the decision tree logic because the aircraft's configuration is predefined for each segment of the profile.

Although Table 9 was developed from an analysis of the C-141A IAT mission type logic, it is presented here to illustrate a generalized approach for transports and bombers and is discussed in more detail in Section VII. The top row of Table 9, identifies the logical events and/or activities. The listed set of logical events/activities and the input parameters (second row) are not intended to be considered as final since they would vary according to the nature of the aircraft and its composite mission history. For example, the transport's cargo weight and cargo airdrop logical event categories would be replaced by weapons weight and weapons delivery logical event categories for the case of a bomber.

In the second row (Table 9) the input (usage) parameters required to determine the occurrence of the logical events/activities are identified; the third row lists the sensors, transducers, and instrumentation required to record the input parameters. There exists, in the parameter list, a degree of redundancy since many of the logical events/activities can be determined using only a few of the listed parameters.

Spectrum Severity Effects

If the aircraft's design load spectrum is decomposed into four component spectra representing degrees of severity (mild, moderate, rough, and severe), then a crack growth analysis could produce different results depending on whether the composite design spectrum or a particular mix of the four component load spectra was used as input. The primary factor affecting the results is the reaction of the analytic crack growth retardation model to the various possible ways of sequencing the components of the load spectrum. This conclusion was reached as a result of a spectrum severity sensitivity study (Reference 27, Section 9) and is discussed below.

Usually, a stress occurrence spectrum is developed for the basic flight load history unit, which in this case is the mission segment. If the mission type spectrum is built up by chaining together a number of segment spectra then a specific crack growth rate (incremental crack length per mission type) will be predicted. However, it can be recognized that each segment's load spectrum is in reality a cumulative sum or probability of occurence of all loads supposedly experienced in that segment (over a long period of time, say 1000 hours or one lifetime), and thus on a per flight hour basis, the segment's spectra must be considered to be an average representation. The segment's single spectrum can be decomposed into component spectra representing the load environment for mild, moderate, rough, and severe flight environments. Experience based on collected flight data indicates that each of these four classes of load environment severity will occur randomly but with a definable probability. Therefore, a conceivable alternate way of constructing a mission type spectrum would be to incorporate a mission segment's contribution on the basis of the probability of the severity class occurring. Ultimately whether using an "average" spectrum, or a spectrum containing four separate components to represent a mission segment is not the most important factor. The real problem is to rationalize the method of selecting and sequencing the stress levels from the segment's spectrum. Crack growth retardation effects used in the analytic model will be affected by any scheme which impacts the selection and ordering of the stress cycles within the mission type stress history.

There are also secondary problems which may be important for IAT programs. They relate to the probability that the flight load severity is dependent on or influenced by the aircraft's home base, the season of the year, the predominate mission type flown, etc. For example, gust loads experienced during the cruise segment may be very severe over a certain geographical region. Should a particular aircraft do a considerable amount of flying in that region, its gust spectrum history will be different both from that of an aircraft flying the same type of mission in regions of less severe gust environments and from an aircraft experiencing the average gust environment history. Therefore the severity problem has two aspects: (1) how the stress spectra severity is to be accounted for in the development of the parametric crack growth analysis, and (2) how the stress spectra severity is to be accounted for within the individual

aircraft tracking program. The second aspect of the problem is of greater interest because an IAT program can be designed to respond to this problem. An IAT program which is limited to using a usage log form as its input can not directly account for flight load severity. The more detailed L/ESS data must be used to backup the spectra development program. The use of an onboard microprocessor IAT system to handle this problem is an obvious solution and will be discussed in Section VII.

Case Study: Rockwell-North American CT-39 Transport

General Description

The IAT Program [29] for the CT-39A/B transport uses a parametric type of cumulative crack growth analysis. The analysis is used to track both the airframe's durability (economic life starting from a crack size of 0.0025 inches progressing to a repair limit of 0.030 inches) and the airframe's damage tolerance life (slow crack growth starting from a crack size of 0.050 inches progressing to critical size, as shown in Figure 22).

The CT-39 force is tracked by means of flight logs. However, use of mechanical strain recorders (MSR) has been proposed. The input data derived from the flight log are used to define the mission profile and the proposed MSR would be used to define the stress history at a critical wing control point. A DADTA was accomplished, and with additional data from full scale fatigue tests and service failures, five control points were selected for crack growth tracking. The most critical control point is at Butt Plane 11 on the wing's lower skin at the front spar. Two control points on the fuselage were selected, one sensitive to vertical gust and maneuver loads and the other sensitive to internal cabin pressure. A control point on the vertical stabilizer sensitive to lateral gust and maneuver loads and a control point on the horizontal stabilizer were also selected. Both the wing control point and the horizontal stabilizer control point are sensitive to vertical gust and maneuver loads. The DADTA load history was developed from several sources. The first was a VGH survey using the A/A24U-10 recorder on twenty-eight aircraft which yielded 15,000 hours of data. This program also supplied flight logs which provided data on mission type, T.O.G.W., T.O. and landing fuel weights, and number of landings. The

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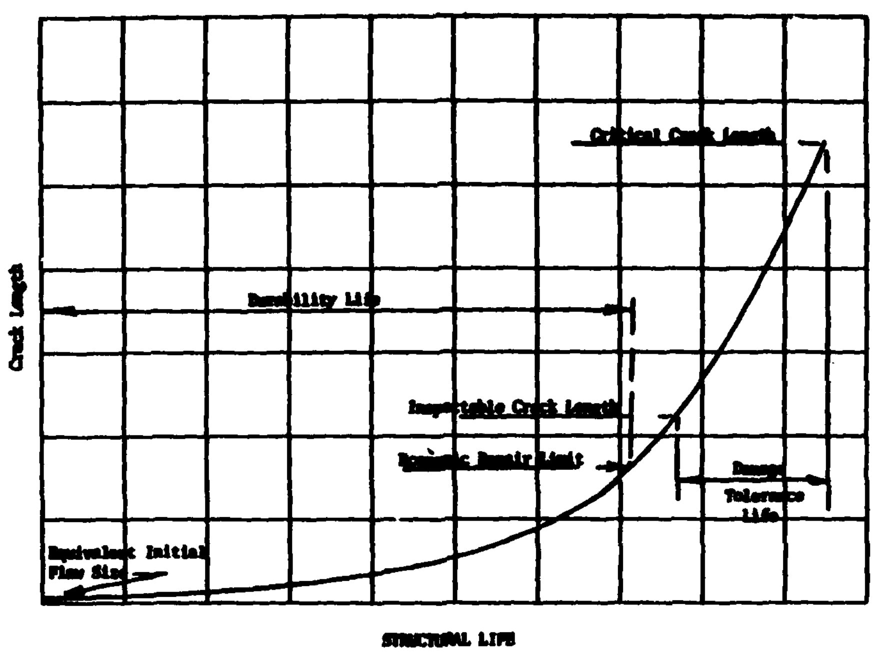


Figure 22. Definition of Crack Growth Life

ROCKWELL INTERNATIONAL — NA-80-265, APRIL 17 1981

ASN: 674471 MDS: CT-39A HOME BASE: RAMSTEIN CMD: MAC A/C HOURS: 14843.6

KEY MAINTENANCE ACTIONS

RPL VT SP CAP 17-39-815 (10289 HR)

USAGE STATISTICS	PERIOD	ACCUM
TOTAL MSNS	10240	10240
TOTAL HOURS	14843.6	14843.6
TOTAL T/G LNDS	4715	4715
TOTAL F/S LNDS	10240	10240
AVG FLT LENGTH	1.4	1.4
AVG TO GR. WT.	17.C	17.0
AVG T/G PER FLT	0.5	0.5

MISSION DISTRIBUTION (% MSNS)

MSN ID	PERIOD	ACCUM
X-CNTRY	89.7	89.7
TRAINING	9.9	9.9
A/C TEST	0.0	0.0
SYS TEST	0.4	0.4
W RECON	0.0	0.0
ABORT FT	0.0	0.0
- - - -	0.0	0.0
- - - -	0.0	0.0
OTHER	0.0	0.0

DAMAGE DATA

	WING	HORIZ STAB	VERT STAB	FUSE LONG	FUSE SKIN
DURABILITY LIFE (HRS)	70291.	152683.	62094.	85182.	44899.
REMAINING DURAB. LIFE (HRS)	55448.	137839.	58300.	70258.	30015.
DAMAGE TOLERANCE LIFE (HRS)	41618.	97952.	61464.	42600.	72926.
REMAINING D.TOL. LIFE (HRS)	26774.	83109.	56909.	27836.	58083.
DURABILITY CRACK LENGTH (IN)	0.00269	0.00272	0.00277	0.00271	0.01058
ECONOMIC REPAIR LIMIT (IN)	0.03	0.03	0.03	0.03	0.05
DAM. TOL. CRACK LENGTH (IN)	0.08938	0.07339	0.05971	0.07697	0.13462
CRITICAL CRACK LENGTH (IN)	0.21	0.55	0.56	0.51	4.00
PERIOD DUR. CRACK GROWTH(IN)	1.9E-04	2.2E-04	2.7E-04	2.1E-04	8.1E-03
ACCUMULATED COMPONENT HOURS	14843.6	14843.6	14843.6	14843.6	14843.6

TABLE 4-1-102 INDIVIDUAL AIRCRAFT TRACKING LOG

Figure 23. Typical IAT Output Parameter Table for the CT-39A/B Transport (Reference 29)

second source of data is an ongoing L/ESS program using the MXU-553 digital magnetic tape recorder system on ten aircraft. The data recorded include aircraft serial number and base, mission type, gross weight at take-off and landing, airspeed (Mach number), altitude, and normal and lateral load factor (n_z and n_y). These data are used to define five different mission type profiles in terms of the steady state mean (n_z = 1g) load and the gust and maneuver incremental load factors (Δg). The external air loads are proportional to the gust and maneuver load factors and are used to calculate the shear, bending moment, and torque loads for the control points.

The MXU-553 data were analyzed to provide information on gust loads (which were defined as peak or valley excursions of less than one second duration) as measured from load factor threshold range of $1.15 \geq n_z \geq 0.85$. Load factor excursions of duration greater than one second were listed as maneuver loads.

The CT-39 is a utility aircraft used as an executive transport and as a training aircraft. The original mission mix in the DADTA used five different mission type profiles and a composite mission type profile [30]. Each mission profile was made up of segments defined by incremental time, weight, airspeed, and altitude. Load factor spectra were developed for each mission segment and each major airframe component. Cycle-by-cycle load factor histories were then constructed for each mission type profile with the loads arranged in a high to low sequence within the segment. A typical mission would include ground (preflight), climb, cruise, pilot proficiency, descent, and ground (postflight) segments.

The crack growth rate equation used in the DADTA was a variation of the Paris equation with a Walker stress ratio correction exponent.

$$\frac{da}{dN} = C\left[\frac{K}{(1-R)^{1-m}}\right]^n \tag{43}$$

The analysis accounts for overload retardation and compression load acceleration. For each structural control point, a load factor to stress relationship was developed and used to convert the load factor histories into stress histories. Load cycles were sequenced using range pair counting of the history.

The DADTA was used to study the impact of usage parameters and their variations as based on recorded L/ESS data. In general, the most predictable parameters were take-off gross weight, airspeed, fuel weight, and fuel consumption. The least predictable major parameters were found to be altitude, duration of the mission, and the number of touch-and-go landings (TAG).

The current IAT program, which starts with the reading of the flight log data, has been implemented through a set of computer programs briefly described in Reference 31.

Description of the Parametric Analysis

As a result of the L/ESS programs and the DADTA [30], seven mission types were identified. However, statistically almost all of the force's missions were limited to two types: cross-country transport, and training. A special TAG "mission type" profile was generated to account for the effect of TAG landings. This mission type is made up of a short approach segment a landing segment and a take-off segment - all of five minutes duration. Both the cross-country and training mission types were subdivided into four maximum altitude population groups and four different mission durations. For example, the maximum altitude bands are zero to 8 Kft, 8 Kft to 15 Kft, 15 to 25 Kft, and 25 to 35 Kft. The end result is that there were 16 different cross-country mission type profiles, 16 different training mission type profiles, and one TAG landing profile (See Table 10). The parametric crack growth analysis is based on these 33 mission type profiles. A crack growth history (crack length versus occurrences of a specific mission type) was developed for each structural control point [31]. These parametric relationships are part of the data library of the IAT computer program. There also is a library of aircraft identity data and crack size/control point data. For any given control point and current crack length, the appropriate crack growth curve for the detected mission type (with the proper maximum altitude and duration) is entered to determine the incremental crack growth for that mission type occurrence. If the actual duration of the detected mission is different from that of the mission type profile, the crack growth is determined by interpolation of the damages for

TABLE 10. PARAMETRIC DEFINITION OF THE THIRTY-THREE CT-39A/B MISSION TYPES

SUMMARY OF FLIGHT PROFILES FOR IATP

Mission Type	Take Off Gross Wt. (kips)	Max Flight Altitude	Flight Length (Hrs)					
			3.0	2.0	1.5	1.0	0.5	0.1
Cross Country	17.0	35.0	X	X		X		X
	"	25.0	X	X		X		X
	"	15.0	X	X		X		X
	"	8.0	X	X		X		X
Transition/Training	"	35.0	X		X		X	X
	"	25.0	X		X		X	X
	"	15.0	X		X		X	X
	"	8.0	X		X		X	X
Touch and Go Landing	13.5	2.0						X

X denotes the profiles used when generating IAT crack growth library.

Reference 29.

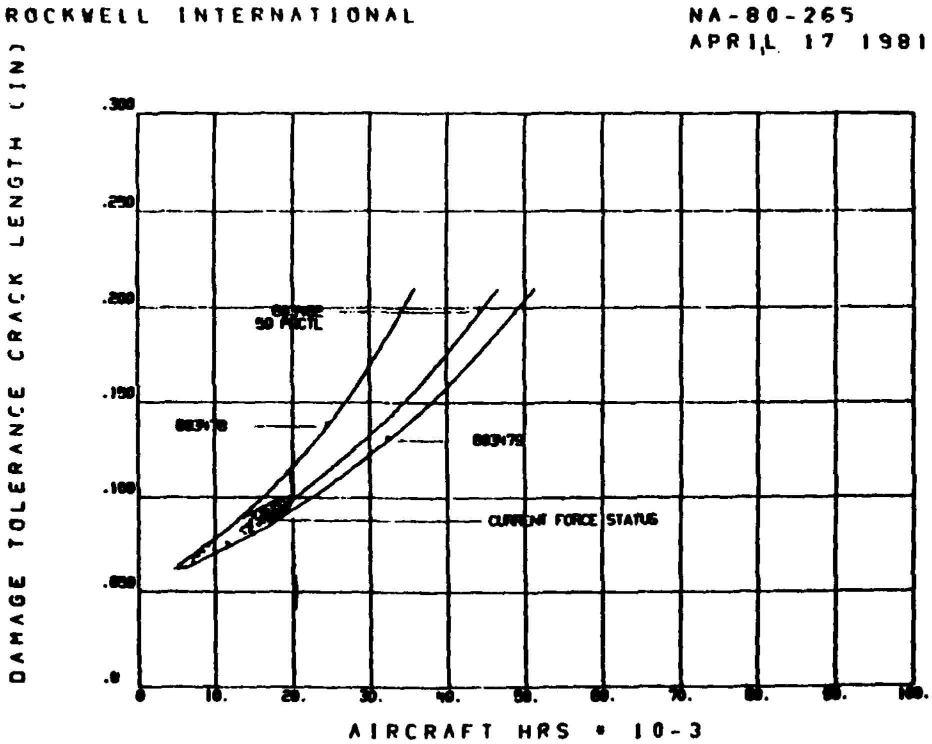


Figure 24. Predicted and Current Damage Crack Growth for the Wing Control Point (Reference 29)

mission types of standard durations which bracket the actual duration. If a TAG landing occurred, the TAG profile curve would be entered to find the incremental crack growth and five minutes of duration would be subtracted from the actual mission duration.

As discussed above, the IAT program tracks two different cracks: (1) a durability/economic life crack with an initial size of 0.0025 inches and (2) a damage tolerance crack with an initial size of 0.050 inches. The same parametric analysis applies to both, so tracking of the two cracks is merely an exercise in bookkeeping.

IAT Input Parameters

The primary input is the AFTO Form 166 flight log which is filled out by a crew member to provide the following data:

1) Mission type
2) Mission duration
3) Take-off gross weight
4) Maximum altitude
5) Maximum airspeed
6) Fuel consumption
7) Number of landings.

In addition, aircraft identity and associated data are provided. Of these input parameters, the ones used in the IAT program are mission type, mission duration, maximum altitude, and number of landings. The computer program logic need only use these parameters to identify the mission type crack growth data sets to be used in the IAT analysis.

IAT Output Parameters

A typical set of output parameters for a specific CT-39 aircraft is shown in Figure 23.

Note that the given predicted durability lives and damage tolerance lives are based on the use of the DADTA baseline spectrum.

The major output parameters are:

1) Remaining and predicted durability life

2) Remaining and predicted damage tolerance life

3) Current durability and damage tolerance crack length

4) Crack growth during the reporting period (usually six months)

5) Accumulated component hours.

Mission distribution data, total hours, total landings and average gross weight are also provided.

Accumulated flight hours and missions are provided in the form of bar charts as well as tables. To identify and alert the force manager to the worse cases, several tables are provided for each control point for the twenty most damaged aircraft. The twenty least damaged aircraft are also identified.

To facilitate visualization of the crack growth status for each control point, a crack growth graph (Figure 24) is generated and it shows:

1) The predicted crack growth for the aircraft having the longest and shortest lives

2) The predicted crack growth for aircraft having a median life, and

3) The current status of the entire force.

Inspection requirements are specified in the Force Structural Manitenance Plan and currently do not appear in any IAT documents. Inspection, repair, and replacement recommendations have already been made as a result of the original DADTA effort. It appears that the IAT program has had little impact to date on the FSM plan. However the IAT program will probably be used to determine which aircraft are to be modified first.

4. Case Study: Boeing C/KC-135 Transports

Background

Boeing/Wichita has studied several types of IAT and crack growth programs for the C/KC-135 transport force [Reference 10]. Their approach was to: (1) evaluate the effects of usage parameters on crack growth models, (2) develop several IAT procedures, and (3) evaluate techniques for implementing the IAT program. All but one of the IAT methods evaluated were based on parametric methods. The usage parameter crack growth study examined the impact of the usage load parameters on three crack growth models: (1) Wheeler, (2) Willenborg and (3) Willenborg/Gallagher.

Description of the Parametric Analysis Methods

The parametric methods were based on either flight log data or MSR data and since they are also described in Reference 4 they will be only briefly described here.

Parametric Crack Growth Rate Table Methods

In this method(s) the data taken from the flight log are used to either identify individual mission segment types or individual mission types and the time increment for each segment type or mission type. The appropriate crack growth rate table for the current crack size is then entered and the unit crack growth rate (da/dt) is determined. The crack growth for the flight is then calculated using the growth rate and the flight time increment. Boeing evaluated the segment type method against the mission type method and found that the mission type method is sufficiently accurate provided the force missions are highly stereotyped. For the cases studied the crack growth histories based on segment type and mission type parameters were very similar.

Parametric Stress Exceedance Method

This method uses the flight log to identify segment types and the time intervals for each segment type. Once the segment type is identified, a predetermined stress exceedence curve (or table) is accessed. The stress history for

termined stress exceedence curve (or table) is accessed. The stress history for the flight is then constructed by stringing together the stress histories for each segment occurring in the flight. Of course the segment stress history is based on the actual time spent in the segment. The mission stress history is then input into a crack growth program which calculates the incremental crack growth (starting from the current crack length) for the mission.

Mechanical Strain Recorder Method

Two approaches are possible using the MSR as the basic usage data acquisition method. In the simplest approach, the MSR data are read off the MSR tape and converted to a stress history using the appropriate transfer function for the structural control point. This stress history is then run through a crack growth program to determine the incremental crack growth based on a cycle-by-cycle analysis. This method is not a parametric type of analysis. However, there is an alternate method of using MSR data in a parametric type of analysis. A series of usage mission/segment stress exceedence data sets are built up to cover the full range of major usage parameters such as high, medium, and low take-off gross weights versus mission type, mission duration (long and short), and degree of severity for each of the segments in the mission types. The segment exceedence curves are used to construct both a composite mission type exceedence curve, and a stress history for the composite mission type. Each parametric usage variation (for example: flight TOGW, long flight duration, and severe usage) is then used to generate a crack growth curve, thus resulting in a family of crack growth curves and associated composite stress exceedence curves for all of the usage models. The aircraft's MSR data for a given usage period are converted to a stress exceedence curve, normalized to the standard time period for the parametric curves, and then compared with the parametric stress exceedence curves. A crack growth curve may then be interpolated between the existing standard composite mission crack growth curves based on the relationship between the aircraft's MSR composite stress exceedence curves and the standard usage composite stress exceedence curves. The disadvantages of this method are obvious. First, the interpolation and analysis can get complicated, and secondly, the accuracy depends on the ability to predict the actual usage

models. This method would negate one of the chief advantages of the MSR; that is, the MSR gives a direct record of the aircraft's usage.

Impact of Input Parameters on Crack Growth Models

Boeing performed extensive analyses and tests to evaluate the three crack growth models chosen for the study. All of the models incorporated retardation concepts. The central problem reduces to determining which model can be most reliably and simply adjusted to match the aircraft test results.

Boeing test results [Reference 13, page 31] indicate that the Willenborg/Gallagher model using an overload ratio of 2.5 for aluminum produced results similar to the Wheeler model using an exponent factor (m) of 0.90. However, it is claimed that the Wheeler model is easier to correlate with test results. Furthermore, it was determined that the selection of the retardation model and its empirical factors is highly dependent on the spectrum content or severity of usage. Therefore, each type of aircraft usage must be studied in order to select the retardation model and the values of their empirical factors.

IAT Input Parameters

To develop the parametric analysis, seventy flight conditions representing five mission segments were selected. The segments are climb, low level flying, cruise, refueling, and traffic pattern flying (which includes TAG landings). Eleven different gross weights were used but not for all of the 5 segments. Three altitudes were considered for the cruise segment. The actual usage parameters and mission segment types affecting crack growth are shown in Table 11. The results of the Boeing analysis showed that gross weight and altitude were the two greatest influences on crack growth for the wing and fuselage.

The flight log form (AFTO-76 Form) lists six operation phases: climb, cruise, fuel on-load, fuel off-load, descent, and traffic pattern. The clock time, altitude, fuel weight, and airspeed are listed for each phase. The takeoff fuel, cargo, and gross weights, aircraft hours and flight duration are also listed as are the number of landings (TAG and full stop). If a MSR is

used either with or without the flight log then a strain history will be added to the list of input parameters.

IAT Output Parameters

Little specific data are available relative to the selection of output parameters. Obviously, they would not be very different from those of other aircraft. Because of the log-linear relationship existing between crack length and crack growth rate, the calculation of predicted crack growth lifetimes is facilitated and the time remaining to the safety limit or economical repair limit may be expressed as:

$$t = \frac{a_i^{1/s}}{\left(\frac{da}{dt}\right)_i} \left[\frac{S - 1}{S}\right] \left[a_f^{\frac{S-1}{S}} - a_i^{\frac{S-1}{S}}\right] \qquad (44)$$

where

t = time to grow from a_{i-1} to a_f

a_i = current crack length

a_f = final crack length

$\left(\frac{da}{dt}\right)_i$ = crack growth rate from the last or i^{th} period

S = slope of the crack length versus da/dt curve for the projected usage

This brief description [10], shows that the major output parameters are:

1) Initial crack length
2) Current crack length
3) Current crack growth rate
4) Slope of the crack length versus crack growth rate curves for projected usage
5) Predicted final crack length and
6) Normalized crack growth curves.

TABLE 11. USAGE INPUT PARAMETER AFFECTING CRACK GROWTH FOR MAJOR COMPONENTS OF THE AIRCRAFT

USAGE PARAMETER OR MISSION SEGMENT TYPE	KC-135 AIRCRAFT COMPONENT				
	WING SKINS		FUSELAGE	VERTICAL STABILIZER	HORIZONTAL STABILIZER
	UPPER	LOWER			
GROSS WEIGHT	X	X	X		X
AIRSPEED		X	X	X	X
ALTITUDE		X	X	X	X
CENTER-OF-GRAVITY LOCATION	X	X	X		X
WEIGHT	X	X	X		X
CABIN PRESSURE	CENTER WING		X		
CLIMB	X	X	X	X	X
CRUISE		X	X	X	X
LOW LEVEL		X	X	X	X
LANDING	X	X	X		

SECTION VII

ADVANCED CONCEPTS USING MICROPROCESSOR BASED IAT SYSTEMS

The background data discussed in previous sections indicates a number of possible system concepts for μP-based IAT systems. In this section a number of candidate concepts are described more fully in terms of functions and hardware. A generic IAT and L/ESS system and other systems with limited or special functions are described in Subsection 2. Two IAT μP systems explicitly designed for the two classes of aircraft are described in greater detail in Subsections 3 and 4. Input and output parameter requirements are discussed in Subsections 5 and 6 and Force Management aspects are covered in Subsection 7.

1. Desired Characteristics of a Microprocessor-Based IAT System

Discussion of Basic Characteristics

The microprocessor (μP)-based IAT system should have the following characteristics, some of which may at this time be difficult to achieve:

(1) Inexpensive
(2) Fits into many different types of IAT programs
(3) Has the capacity to perform many diverse functions
(4) Simple to program and use
(5) Reliable

Because of the wide range of existing IAT programs, it is obvious that the first generation μP systems should have the capability to fit into the existing programs with a minimum of program revision. This capability does indeed exist. Furthermore, the μP has this capability because it can be

programmed to perform a variety of different IAT programs. The currently available μP devices, when integrated into an IAT μP system, have all the above desirable features except inexpensiveness. It must be recognized that while the individual μP chip device is relatively inexpensive, it is the total μP system (data acquisition, data retrieval and data transmittal subsystems) which is expensive. This report does not address the problem of system costs.

The major factor leading to high system costs is the relative immaturity of the IAT μP system technology. It is reasonable to expect that μP system costs will drop as the system technology is developed by industry and the USAF and as the semiconductor industry develops more powerful μP devices.

Hardware/Software Commonality

Because of the current level of technological maturity, it is doubtful that the first generation IAT μP system could be established from off-the-shelf type of hardware. The potential is there and all of the advanced concepts discussed in this report have been considered with the idea of commonality in mind. The expected problems are due to (1) the lack of a specified standard programming language, (2) the handicaps imposed by the cost of system memory, (3) the system costs of integrating the μP system with the selected usage parameter data acquisition hardware system and devices, and (4) system software development.

Candidate Concepts for IAT Systems

The candidate concepts considered in this study fall into only two general categories without regard to class of aircraft:

Concept 1: The onboard μP system functions solely as a usage input parameter acquisition system.

Concept 2: The onboard μP system functions as a usage input parameter acquisition system, as a damage tolerance analysis system, and as an output parameter system.

Candidate Concepts for L/ESS Systems

Two basic concepts were studied and are discussed:

Concept 1: The μP-based L/ESS system is limited to the recording function analogous to currently used multi-channel recorders.

Concept 2: The μP-based L/ESS system analyzes the input parameter data as they are acquired thus performing some or all of the analytic functions normally performed on large computers.

2. Review of Advanced Concepts for IAT and L/ESS Microprocessor Systems

Introduction

The major advantages of a microprocessor based IAT or L/ESS system are its capacity to extend or amplify the force manager's and system designer's logical control over much of the system's operations, reduce onboard and offboard data processing workloads, reduce the pipeline time for some operations and improve data reliability. A secondary advantage is the capability of the microprocessor based IAT or L/ESS subsystem to fit into existing IAT or L/ESS programs with little or no change in its functional concepts.

Current IAT and L/ESS systems are organized into a series of automatic or semiautomatic subsystems which can only be operationally linked by various manual activities [4]. While human intervention is necessary and desirable for evaluation and control purposes at the higher echelons, the manual effort currently required at the lower operational echelons is excessive. Studies of various current systems indicate that excessive man hours are used to acquire data, transmit these data at the tactical activity echelon, and to process them at the higher echelon. In addition, time and effort must be expended to perform the computational tasks required by the IAT programs. Manpower and priority problems have also resulted in the reduction of the amount of processed force usage data (as compared to the amount of data theoretically collectable), lower data reliability, and in increased turnaround time for the required IAT and L/ESS program data outputs.

All of the above problems can be attacked, and to some extent solved, by designing future IAT and L/ESS systems which use onboard microprocessors to perform as many of the manual activities and main frame computational activities as possible. However, while a microprocessor based system can significantly reduce the manual workload, it can not eliminate it. Further reduction in manual workload can only be accomplished by the incorporation of additional automated data processing subsystems in the current manual subsystems. In this respect, the most difficult technical and logistical problem (in terms of reducing manual effort and the timely and economic transmittal of data) is the problem of retrieving and transmitting data from the aircraft to the responsible ALC.

System Functional Description

The system description in this section will apply to L/ESS systems as well as IAT systems without distinction unless noted. Furthermore, the described system shall be considered to be a generic system structured to accomplish all IAT and L/ESS functions. Since the actual IAT system designed for a particular aircraft can be integrated with existing onboard sensor, transducer, and instrumentation subsystems, the front end of the IAT system (data sensing and input) is highly variable in terms of its design and functions. The advisability of integrating the IAT input instrumentation system with the existing aircraft air-data system must be considered for purposes of economy and depends on such factors as the need to isolate the various electronic systems for operational reliability. This question can not be answered here since the answer is dependent on the individual aircraft type and on electronic system design management policy.

The major functions of a generic IAT and/or L/ESS system are outlined in Figure 25. The initial functions (1A and 1B) are data acquisition and need no further explanation except that they are required to deliver digitized data to the μP. The functions internal to the μP system are processing and storing of data as required by the program which controls the μP and the rest of the system. Depending on the nature of the IAT μP computer program, the processed data stored in the μP may be either the final IAT output data or IAT input data

which are to be passed on for further processing on the ground. The minimum required offboard system capabilities are represented by functions (3) and (6) of Figure 25. These refer to the retrieval of the onboard data by some electronic means and subsequent transmittal to the next logical activity. The maintenance checkout function (8) is extremely useful since it will greatly reduce the time needed to detect hardware manfunctions. Functions (4) and (7) which are needed to change the onboard computer program or to change specific data items (such as initial crack length, material property parameters, etc.), are desirable for some types of IAT μP systems. The quick-look review function (5) may be needed for some IAT programs but not for others.

The various IAT μP concepts discussed in this section follow the above generic functional structure to varying degrees. The Northrop STEMS™ (a prototype IAT μP system) for the Fairchild Republic A-10A attack aircraft served as a model for the functional diagram [35].

System Hardware Description

The following is a description of a hardware system which is capable of performing the functions outlined in Figure 25.

For the purposes of this investigation, the microprocessor-based IAT system is defined as having three major subsystems: (1) the onboard data acquisition system, (2) the onboard central data processing system and (3) the offboard data retrieval system. The second system is the core of the μP-based IAT system and is referred to as the microprocessor unit or system. Its major components are: (1) the microprocessor, (2) auxillary memory, (3) a data input alphanumeric keyboard, and (4) a power unit. A generic hardware system patterned after the above concept is shown in Figure 26.

The data acquisition function is typically implemented by a varity of sensors, transducers, standard aircraft instrumentation subsystems, a group of signal conditioning units (one for each data channel), a multiplexer, and an analog-to-digital (A-D) converter. An alphanumeric keyboard is also needed so that a flight or ground crew member can input data which cannot be obtained, for practical or economic reasons, by instruments. Data such as cargo weight and the number, type, and weight of external stores fall into this category.

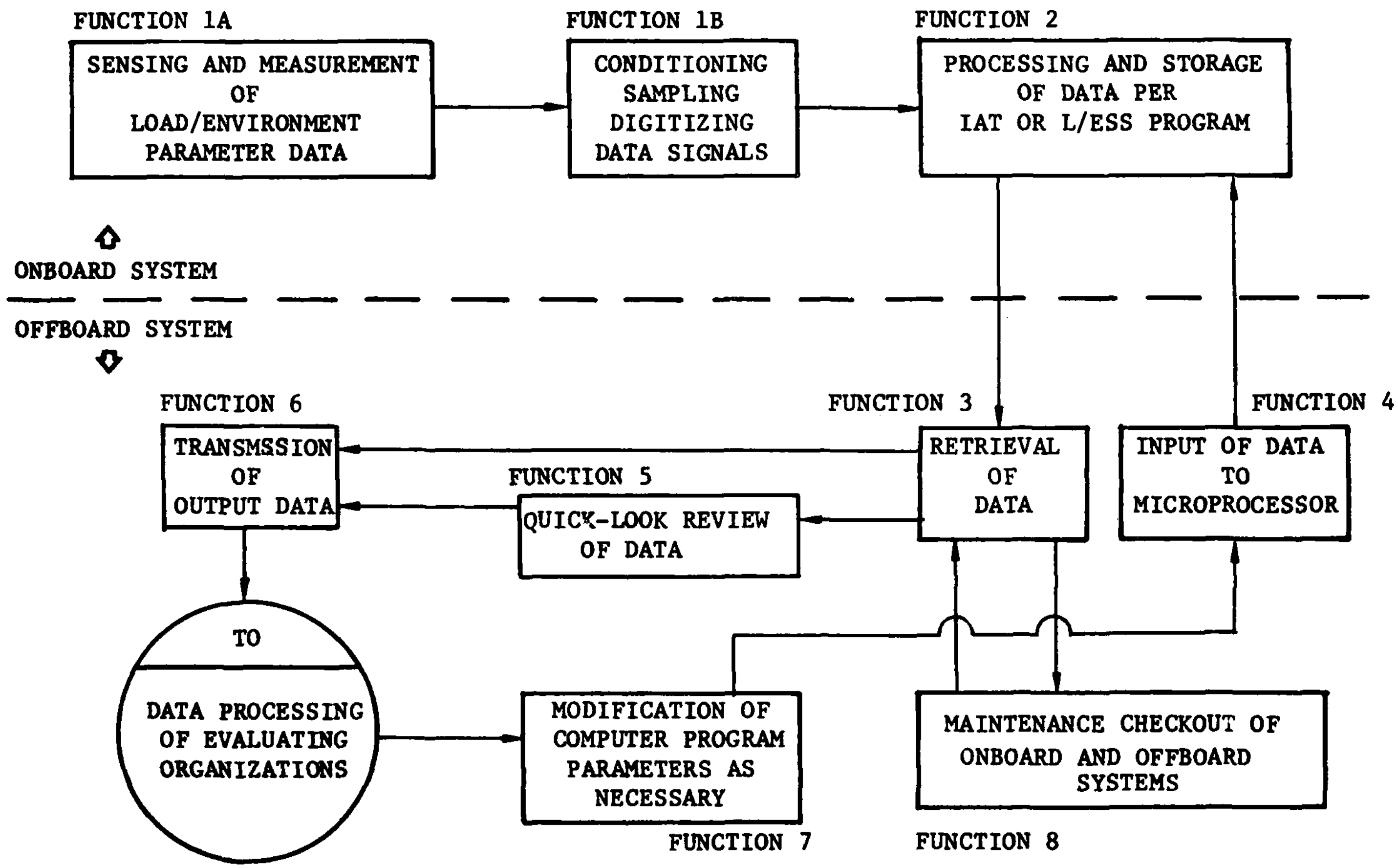


Figure 25. Major Function of a Generic IAT and L/ESS System

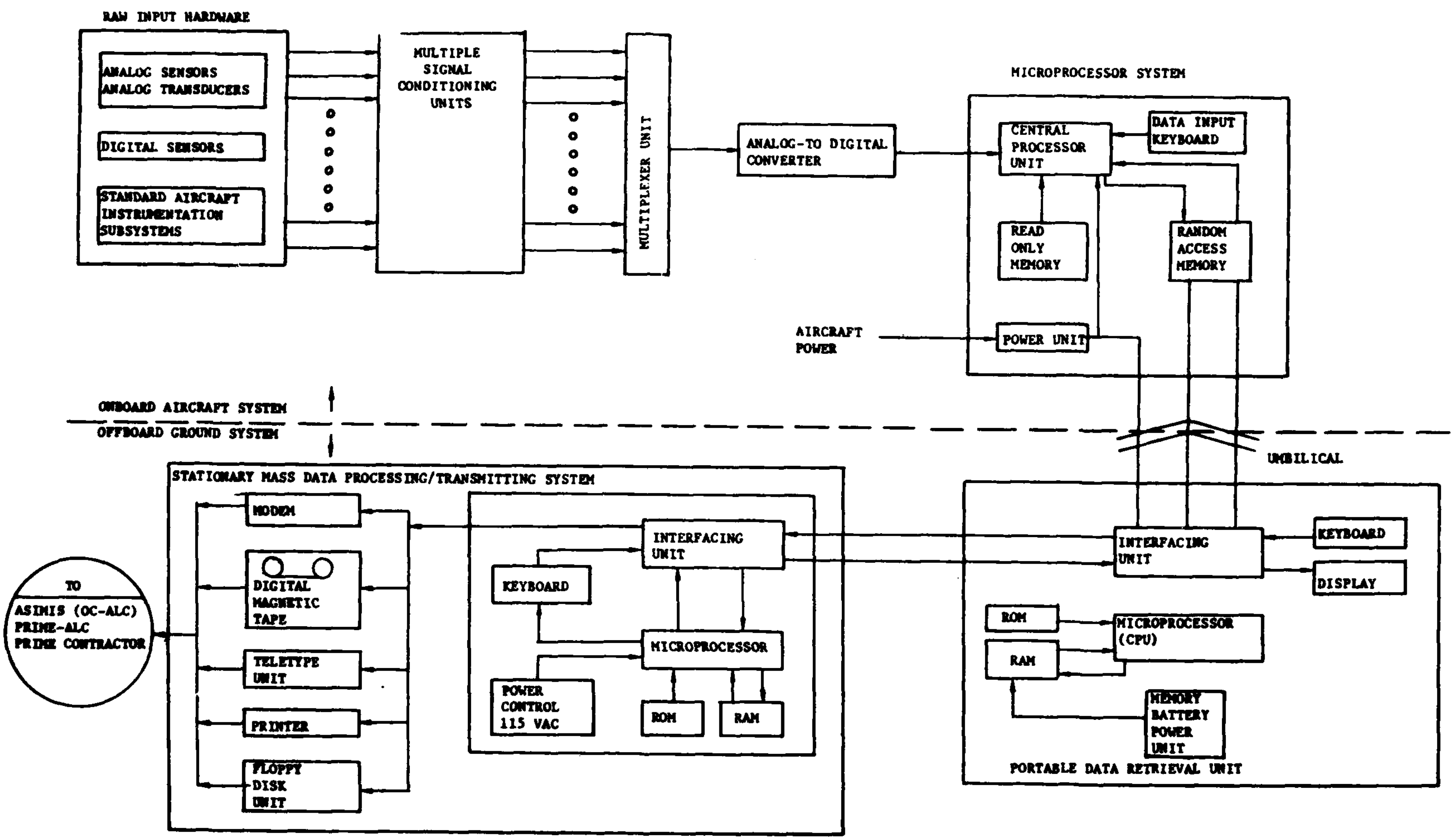


Figure 26. Typical Microprocessor-Based IAT or L/ESS System Onboard and Offboard Hardware

The number and type of data acquisition channels will depend on the nature and purpose of the specific aircraft IAT or L/ESS systems and could vary from one data channel to 20 or 30 channels.

Both analog and digital sensors and transducers may be used. Digital sensors are defined as on-off sensors which signal the existance or occurrence of an event; for example, a weight-on-wheels sensor which signals a landing touch-down or take-off. Analog transducers and sensors are devices which output analog electrical signals (varying voltage) to signal quantities such as angular position of a control surface, the resistance of a electrical resistance strain gage, the linear normal acceleration force, airspeed, etc.

Since many of the aircraft response parameters and some of the aircraft configuration parameters are already sensed by various standard instruments and electronic subsystems, there usually is little technical reason for not tapping into such circuits to access the flight parameters and eliminating or reducing special IAT or L/ESS data acquisition instrumentation. A considerable amount of system cost can be tied up in such instrumentation.

The raw input signals are fed to a series of Signal Conditioning Units (SCU) to scale each of the analog voltage signals and to provide a calibrated output. For example, the SCU converts the strain gage resistance signal to a voltage signal which is proportional to the value of the measured strain. Each raw input parameter signal will have its own signal channel and SCU. In general, each SCU must be selected and/or designed to fit the needs of the particular data signal being monitored. For example, an SCU for strain gages must have circuitry to supply power and balance the strain gage circuit while a SCU for airspeed may translate the voltage and filter out the higher frequencies.

After conditioning, the various input signals are channeled to a multiplexer which determines the sampling rate for any particular data channel and sequentially selects for processing each data channel according to some logical rule. While there are many data channels monitored by the multiplexing unit (about 40 data channels on the A-10A STEMS™) only one data channel at a time is transmitted downstream to the μP system.

The signals then go through the analog-to-digital (A-D) converter which samples the analog voltage signal at fixed time intervals and converts the voltage value to a digital signal for the μP.

The digital signal is then processed by the μP which temporarily stores each digital signal until sufficient samples have been accumulated for the μP to logically identify an event of interest. For example, in order to enable the μP to identify a load factor peak, a series of load factor digitized values, representing the load factor amplitude at every tenth of a second, are temporarily stored as the data are received. After a fixed length of time, (a few minutes or less), the μP scans all the load factor amplitude values in temporary storage and identifies the highest value as the load factor peak. The time parameter is also available for correlation of the peak load factor with time.

In general the μP system moves, compares, stores, and manipulates data. After performing all of the real time and non-real time data manipulation required by the computer program which controls the μP system, the system then stores the processed data until the aircraft returns to its base and the data are retrieved by use of a portable ground based system.

The conceptualized microprocessor system hardware is made up the following components: (1) a single microprocessor chip containing the usual arithmetic and logic unit, control units, Read Only Memory (ROM) unit, program/instruction counters, small scale Random Access Memory (RAM) unit, etc., (2) an auxiliary solid state off-the-chip data memory (RAM) and (3) an auxiliary solid state off-the-chip program memory (ROM), (4) a power unit using, during flight operations, standard aircraft AC power and a rechargeable battery pack to maintain the ROM when the aircraft's power supply is shut down on the ground, and (5) an alphanumeric key board mounted either in the cockpit or in a location easily accessible on the ground which can be used to key-input data not provided by the normal data acquisition instruments. A typical μP is the commercially available 8-bit Intel 8085A. Devices of this type usually contain a very limited amount of program and data memory on the chip (of the order of 256 to 4000 bytes). For this reason, off-the-chip memory is mandatory for both IAT and L/ESS purposes, which - depending on the tasks designed for the IAT μP - generally require 10K bytes or more. Significant progress is now being made

in designing and fabricating denser μP chips with more memory circuits, and it is likely that single chip microcomputers may be available in the future which could handle very simple IAT programs. However, current state-of-the-art hardware will normally require off-the-chip memory (ROM and RAM).

The ground system portion of the μP IAT system in Figure 26 is sophisticated, and several simplified system variations are possible at the expense of performance.

The portable Data Retrieval Unit (DRU) should be physically small and light so that it can be slung from a man's shoulder and easily carried out to the aircraft where an electrical umbilical cable is attached to retrieve the data. The Data Retrieval Unit conceived in this generic system would be controlled by its own μP (similar to the onboard μP) and would have sufficient programming memory to function as a microcomputer and sufficient data memory to retrieve and store IAT and L/ESS data from a number of aircraft. The number of aircraft that can be serviced during one visit to the flight line depends on the amount of data retrieved from each aircraft and the memory size of the DRU. When the DRU memory is filled up, the unit must be returned to the stationary bulk data processing/transmitting system to drain off the aircraft data.

The DRU should have a simple keyboard for several operator commands such as (1) start/stop data retrival, (2) transfer data, (3) check out of the onboard IAT system status, (4) self-check of functional status, and (5) check out of the battery power level. A simple display panel using light emitting diodes (LED's), or liquid crystal display (LCD) would be needed to indicate various system conditions. Normal operating power may come from the aircraft through the umbilical cable. However an internal battery is required to maintain the memory system when the DRU is free of the aircraft's or ground power systems.

An alternate data retrieval concept to that shown in Figure 26 is the use of a memory cassette system. In this concept the aircraft would have an easily accessible cassette receptacle as part of its data output hardware system. To retrieve the aircraft's IAT data, a memory cassette is manually

inserted into the aircraft's cassette receptacle and the data are then transferred to the cassette. End of data transmission is indicated by an appropriate signal and the cassette is manually removed. The memory casette is then carried to the on-base stationary bulk data processing station where the individual aircraft data are consolidated for later bulk data transmission.

The memory cassette may be either a CMOS solid state memory device or a bubble memory device. The design and selection of the memory cassette depends on requirements such as: data storage capacity, ruggedness, size, weight, transportability, etc. Bubble memory cassettes are commercially available, although at this time they may not be able to meet military specification requirements.

Another alternate data retrieval system would be a portable floppy disc recording system. Floppy disc devices have the advantage of being able to store very large amounts of data compared to the solid state memory unit in the portable DRU or the memory cassettes.

The IAT ground support system will require a non-portable bulk data processing and transmitting system which would normally be located in the maintenance organization's office. The function of this system is to retrieve the IAT and L/ESS data from the portable DRU's, process the data as necessary, store the data temporarily, group new data with like data, print a quick-look version of the data for use by the local maintenance personnel, and finally, periodically transmit the collected data using some means of bulk data transmission. The system should include a μP for programming and control purposes, a solid state memory for program and data storage, a key board for operation commands, and one or more data transcription or transmittion units such as a telephon modem, a digital magnetic tape device unit, a teletype unit, a printer, or floppy disc recorder. Of the five types of data transmittal units, the teletype and the telephone modem are the slowest if large amounts of L/ESS data are to be transmitted. Estimates indicate that the amount of data collected in one flight hour (with 30 parameters sampled at the rate of ten times a second) may require two or three hours of telephone transmission time. This estimate does not include the beneficial effects of some form of data compression. While the telephone modem and the teletype (which has a slower

transmission rate) are not efficient for L/ESS data, they will probably be adequate as a means of transmitting IAT data since the amount of the IAT data is much less.

The hard copy printer is a relatively inefficient means of moving data for several reasons. Printed output is cumbersome to transmit, to store, and later, to retrieve data from.

The best means of data transmission are the magnetic tape and floppy disk units. Both media can transmit large amounts of bulk data reliably and quickly. Furthermore, the media are obviously adaptable to being integrated with other computer data systems. The generic system outlined in Figure 26 requires that the recipient of the data (whether it is USAF's ASIMIS organization, the air logistic centers, or the prime contractor) will have computer facilites capable of using magnetic tape, floppy disk, or telephone modem means of bulk data transmittion.

Variant IAT Systems

A number of different IAT systems can be developed to satisfy the two basic functions of IAT data acquisition and analysis. These systems are referred to as:

(1) IAT Statistical Parameter Recorder

(2) IAT Flight Log Recorder

(3) IAT System

(4) IAT Combined Flight Log and Statistical Parameter Recorder, and

(5) Combined IAT and Statistical Parameter System.

These five system concepts are listed in Table 12, which describes each system's onboard function and type of output from the onboard part of the system, and (on the second part of Table 12) the type and function of the ground based part of the system as well as the type of crack growth analysis program which could be used to support the IAT program. These IAT systems satisfy one of the three functional uses:

TABLE 12. SYSTEM OUT AND FUNCTIONS FOR THE ONBOARD AND GROUND BASED SUBSYSTEM FOR EIGHT TYPES OF MICROPROCESSOR BASED IAT AND L/ESS SYSTEMS

SYSTEM	TYPE OF ONBOARD AIRCRAFT MICROPROCESSOR SYSTEM	ONBOARD AIRCRAFT SYSTEM	
		FUNCTIONS	TYPE OF SYSTEM OUTPUT
1	IAT STATISTICAL PARAMETER RECORDER	MONITOR, RECORD, AND STATISTICALLY PROCESS RAW USAGE DATA NEEDED AS INPUT DATA TO IAT CUMULATIVE CRACK GROWTH ANALYSIS PROGRAM PARAMETER STATISTICAL DATA ALSO SERVES AS A LIMITED L/ESS DATA SET	EXCEEDANCE OR OCCURRENCE TABLES OF: (1) VERTICAL LOAD FACTOR (N_z) (2) LATERAL LOAD FACTOR (N_y) (3) STRESS PEAKS/VALLEYS (4) STRESS OR LOAD FACTOR RATIOS (5) OTHER MAJOR RESPONSE/FLIGHT/ CONFIGURATION PARAMETERS PARAMETER CORRELATION OCCURRENCE TABLES: (1) VERTICAL LOAD FACTOR VERSUS ALTITUDE (2) OTHER
2	IAT FLIGHT LOG RECORDER	MONITOR AND PROCESS RAW USAGE DATA IDENTIFY THE KEY USAGE/INPUT PARAMETER(S) NEEDED FOR CUMULATIVE CRACK GROWTH ANALYSIS	KEY USAGE/INPUT PARAMETER OCCURRENCES (1) MISSION TYPES (2) NON-STANDARD MISSION (3) MISSION SEGMENT TYPES (4) SPECIAL EVENTS
3	IAT SYSTEM	MONITOR AND PROCESS SELECTED RAW USAGE PARAMETERS TO DETERMINE: (1) STRESS HISTORY (2) REGRESSION EQUATION PARAMETER OCCURRENCES OR HISTORY PARAMETERS o LOAD FACTOR o WEIGHT o AIRSPEED o OTHER CALCULATE CUMULATIVE CRACK GROWTH, NORMALIZED CRACK LENGTH, DAMAGE INDEX FOR ONE OR MORE STRUCTURAL CONTROL POINTS	NOMINAL IAT OUTPUT PARAMETERS (1) CUMULATIVE CRACK GROWTH (2) DAMAGE INDEX (3) EQUIVALENT FLIGHT TIME
4	IAT COMBINED FLIGHT LOG AND STATISTICAL PARAMETER RECORDER	HAS THE COMBINED CAPABILITY AND PURPOSES OF SYSTEMS 1 AND 2 (ABOVE) THE MAJOR PURPOSE OF COLLECTING USAGE PARAMETER STATISTICS IS TO OUTPUT A LIMITED AMOUNT OF L/ESS DATA, THAT IS, THE MOST CRITICAL DATA.	SAME AS SYSTEM 1 AND 2
5	COMBINED IAT AND STATISTICAL PARAMETER SYSTEM	HAS THE COMBINED CAPABILITY AND PURPOSES OF SYSTEMS 1 AND 3 (ABOVE)	SAME AS SYSTEM 1 AND 3

TABLE 12. SYSTEM OUTPUTS AND FUNCTIONS FOR THE SUBSYSTEMS FOR EIGHT TYPES OF MICRO[illegible] L/ESS SYSTEMS (CONCLUDED)

SYSTEM	TYPE OF ONBOARD AIRCRAFT MICROPROCESSOR SYSTEM	GROUND BASED SYSTEM	
		TYPE	FU[illegible]
1	IAT STATISTICAL PARAMETER RECORDER	AIRCRAFT DATA RETRIEVAL SYSTEM BULK DATA TRANSMISSION SYSTEM COMPUTER: MAIN FRAME OR MINICOMPUTER	RETRIEVE DATA FROM[illegible] TRANSMIT DATA TO A[illegible] CALCULATE { DAMAGE[illegible] STRESS[illegible] CRACK [illegible]
2	IAT FLIGHT LOG RECORDER	COMPUTER: MAIN FRAME FOR LARGE IAT PROGRAMS (C-5A) DATA RETRIEVAL/TRANSMISSION SYSTEM	CALCULATE { INCREM[illegible] CUMULA[illegible] ACTUAL [illegible] GROWTH [illegible]
3	IAT SYSTEM	DATA RETRIEVAL/TRANSMISSION SYSTEM	RETRIEVE AND TRANS[illegible] TO VARIOUS USERS: PRIME-[illegible] ASIMIS[illegible] PRIME [illegible] UNIT O[illegible] ORGANI[illegible]
4	IAT COMBINED FLIGHT LOG AND STATISTICAL PARAMETER RECORDER	SAME AS ABOVE	SAME[illegible]
5	COMBINED IAT AND STATISTICAL PARAMETER SYSTEM	SAME AS ABOVE	SAME[illegible]

SYSTEM OUTPUTS AND FUNCTIONS FOR THE ONBOARD AND GROUND BASED SUBSYSTEMS FOR EIGHT TYPES OF MICROPROCESSOR BASED IAT AND L/ESS SYSTEMS (CONCLUDED)

GROUND BASED SYSTEM		TYPE OF CRACK GROWTH ANALYS PROGRAM SUPPORTING IAT PROGRAM
TYPE	FUNCTIONS	
DATA RETRIEVAL SYSTEM TRANSMISSION SYSTEM MAIN FRAME OR MINICOMPUTER	RETRIEVE DATA FROM EACH AIRCRAFT TRANSMIT DATA TO ASIMIS, PRIME-ALC, CONTRACTOR CALCULATE { DAMAGE INDEX, STRESS PEAKS/ VALLEYS, CRACK GROWTH } DIRECTLY FROM REGRESSION EQUATIONS (F-4, A-7)	PARAMETRIC TYPE ANALYSIS TO: DETERMINE REGRESSION EQUATIONS RELATING KEY USAGE PARAMETERS TO DAMAGE INDEX OR CRACK GROWTH REGRESSION ANALYSIS TO: DETERMINE REGRESSION EQUATIONS RELATING STRESS TO KEY USAGE PARAMETERS
MAIN FRAME FOR LARGE AMS (C-5A) IEVAL/TRANSMISSION SYSTEM	CALCULATE { INCREMENTAL CRACK GROWTH, CUMULATIVE CRACK GROWTH, ACTUAL VERSUS PREDICTED CRACK GROWTH RATE PARAMETER }	PARAMETRIC TYPE ANALYSIS BASED ON KEY ACTIVITY PARAMETER LIKE MISSION TYPE NON-STANDARD MISSIONS
IEVAL/TRANSMISSION SYSTEM	RETRIEVE AND TRANSMIT IAT OUTPUT DATA TO VARIOUS USERS: PRIME-ALC FORCE MANAGER ASIMIS PRIME CONTRACTOR UNIT OR BASE MAINTENANCE ORGANIZATION	SAME AS ABOVE
ME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE
ME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE

2

(1) Use the μP for input data acquisition, thus replacing the older type data acquisition hardware systems such as VGH recorders, statistical accelerometer recorders, and strain level counter recorders

(2) Use the μP to electronically generate a flight log using conventional sensors and a minimal number of keyboard entries from the crew

(3) Use the μP for both data acquisition and data analysis functions so as to partially or fully accomplish the IAT task onboard the aircraft.

Use of the Microprocessor System for Data Acquisition

The data acquisition system can be functionally as simple as the conventional electro-mechanical statistical accelerometer or it can be as complex as the commonly used multi-channel recorder where 10 or more usage parameters may be monitored and recorded.

As a simple single data channel "statistical accelerometer," the μP system has many advantages.

(1) The normal load factor peaks and valleys can be accurately defined.

(2) The number of load factor intervals chosen to make up the full range of load factors can be significantly increased, resulting in a finely defined exceedance or occurrence table.

(3) The maximum (peak) and minimum (valley) load factor occurrences can be correlated to provide the proper peak-valley relationship, which is beyond the capability of present day statistical accelerometer devices.

(4) A number of statistical properties of the load factor time history can be calculated. These properties are the mean, mean square, standard deviation, and variance of the cumulative and the individual flight load factor time histories.

Another concept is the use of the μP as an electronic analog of the more familiar VGH recorder. In this approach, the system would monitor the three basic response and flight parameters - airspeed, normal load factor, and altitude. The time histories of these parameters could be processed to provide a series of correlations and associated statistical properties.

Although the actual long term peak-valley sequencing will be lost as the data are processed, the short term cyclic peak-valley sequence relationship is retained. For each recorded maximum, the minimum to maximum ratio will be calculated and stored as a parameter in conjunction with its maximum load factor value.

The use of the onboard μP system to fulfill the data acquisition function (now commonly carried out by means of the manually prepared flight log) is a concept that will fit in with a number of current IAT programs. For large aircraft, the most common type of IAT program is the parametric type wherein the crack growth damage is precalculated in relation to a single activity parameter. For the C-5A, C-141, CT-39 and C/KC-135 transports the key activity parameter is the mission type. With this approach, the crack growth is precalculated for a variety of mission types. Therefore, the task of the IAT program is to first identify mission types and then to calculate the cumulative crack growth caused by the mission types experienced by the individual aircraft. Each IAT program will generally have different methods of determining the parametric crack growth or damage growth rates.

Variations of the activity parameter approach may be categorized as:

(1) Mission Type

(2) Mission Segment Type

(3) Data Block Type

(4) Load Condition Types

(5) Special Tactical Activities or Events.

All of these activity parameters are similiar in regards to their function as IAT input parameters. Mission Type and Mission Segment Type activity parameters are the identfying codes for each particular mission or segment in the parametric analysis. The definition of the Data Block Type activity parameter concept is very close to that of the segment concept. A Data Block is defined as a region in the sky through which the aircraft flies. That is, it represents a fixed load environment defined by altitude, airspeed, and gross weight. The Load Condition Type activity parameter refers to the tracking of discretely defined and identifiable loading conditions. Special Tactical Activities are defined as a series of maneuvers which make up a discrete

activity which is difficult to define in terms of segments or data blocks. Typical special tactical activities would be stop-and-go landings and touch-and-go landings. Events are defined as load histories that are very limited in time duration. Examples would be: air cargo drop, gun firing, and store ejection.

The implementation of a μP-based IAT system for the activity parameter approach is constrained by the amount of data memory available. As the level of detail for the identification of the activity parameter increases the data memory requirements increase.

The minimum system would be one designed only to identify the key activity parameter. The next larger system would be capable of identifying the key activity parameter and calculating the incurred crack growth damage. The feasibility of the second approach requires a trade-off between the complexity of the cumulative crack growth analysis and the amount of onboard data memory which is economically available. For example, the C-5A parametric IAT program uses an array of 120 different mission types. The number and size of the crack growth tables representing 120 mission types will require a large storage capacity even if the analysis is limited to just one structural control point. The tracking of ten control points will increase the memory requirement ten-fold. This rule is applicable in most cases because of the lack of similarity (geometrical) between the various control points. It can be concluded, therefore, that the memory requirements for a C-5A type of program are beyond the capacity of first generation μP systems if the data analysis function is to be carried out along with the data acquisition function.

3. Advanced Concepts for Small Class Aircraft

General Discussion

In considering the differences between large class and small class aircraft, two factors predominate: (1) the methods used to calculate the stress spectra from external load data are different in many cases, and (2) fighter/attack/trainer aircraft experience a greater variety of loading conditions or points-in-the-sky. However, in regards to IAT programs, it must be assumed that a

reliable method is used to relate external load parameters to internal load or stress. Therefore, the methods may be of little significance. The second factor is definitely more important because the load analysis for fighter/attack/trainer (F/A/T) aircraft requires more usage/input parameters to define the greater variety of loading conditions. Furthermore, for F/A/T aircraft having advanced design features such as differential horizontal stabilizers, variable geometry wings, vectored thrust devices, etc., the number of necessary usage parameters is greatly increased. For example, fuselage torque loads will be influenced by the deflected positions of the differential horizontal stabilizers for stabilizer induced roll maneuvers and the resulting fuselage stresses will be different than those caused by pure aileron roll maneuvers. Therefore, to generate the fuselage stresses for both types of rolls, both sets of control surfaces must be instrumented to monitor their deflections. For variable geometry aircraft, the sweep angle of the wings is also a very important parameter in defining the wing stresses. At the same symmetrical pull-up load factor value, the wing bending moment and torque load distributions and the resulting stresses will be very different depending on the angle of sweep.

As a general rule, the more versatile the aircraft's performance and the more complex the aircraft's aerodynamic design, the more usage/input parameters will be required for the IAT analysis.

The advanced concepts discussed in the next few sections are presented only as typical cases. A generic IAT system that can effectively serve all F/A/T aircraft does exist and the present prototype A-10 IAT μP system is a excellent example.

An IAT System (System 3) Description

General Description

This concept has the following characteristics:

(1) The IAT data acquisition function and the IAT data analysis function are both performed by the onboard μP system

(2) The cumulative crack growth (CCG) analysis is a non-parametric type of analysis

(3) The IAT analysis includes all the significant structural control points on all of the major components of the aircraft.

The A-10A STEMS[TM] system is a good example of this type of system. Only the major features of this system concept will be described here. For details not supplied below, refer to Section V.

Input Parameters

The required input response parameters are monitored by sensors while the configuration and flight parameters are manually input via an annunciator button panel. The configuration/flight parameters are needed to identify the mission type and to calculate the initial take-off weight and weight changes during flight. The parameters are listed in Table 13 and can be considered to be typical for conventional F/A/T aircraft.

Output Parameters

For each of the control points, the following IAT output parameters are calculated and temporarily stored for later retrieval.

(1) Cumulative logged flight time by mission type

(2) Current (Primary) damage tolerant crack length

(3) Current time remaining to inspection

By increasing the scope of the μP IAT program, the following additional data can be output.

(4) Damage Index

(5) Repeat all of the above for a secondary crack which tracks

(a) The durability of the structure starting from a very small crack size, or

(b) The damage tolerance life starting from a different initial crack size determined by inspection results.

TABLE 13. TYPICAL MONITORED USAGE PARAMETERS

RESPONSE PARAMETERS		
$n_z * W$	Normal load factor * weight	
n_z		
V	Airspeed	
$n_z * V$		
V^2		
$n_y * W$	Lateral load factor * weight	
$n_y * W^2$		
n_y		
p	Roll rate	Required to calculate the effective lateral acceleration of the center of gravity from n_y data remotely monitored
$\dot{p}$	Roll acceleration	
q	Pitch rate	
$\dot{q}$	Pitch acceleration	
r	Yaw rate	
$\dot{r}$	Yaw acceleration	
H	Altitude	
T	Time	

CONFIGURATION AND FLIGHT PARAMETERS	
Store ejection event Gun firing event Speed brake extension event Power throttle angle	Fuel flow Mission type code

4. Advanced Concepts for a Large Aircraft Class Microprocessor IAT System

Overall Concept

The most obvious concept for the use of a microprocessor-based IAT system is to use it to replace, automate, and consolidate into one functional unit the first three functions of, for example, the current C-141 IAT program (as described above in Section VI and in References 27 and 28). These functions are: the manual preparation of the flight usage log form, the automatic reading of the form for the purpose of input into a data bank, and the use of a computer program to analyze the usage data to predetermine the mission type. After these functions have been fulfilled, the microprocessor will temporarily store for periodic retrieval only those usage parameters required to be input into the fracture tracking computer program. These parameters would normally be:

(1) Aircraft Serial Number
(2) Flight Number
(3) Date
(4) Flight Time
(5) Cumulative Flight Time
(6) Cumulative Number of Full Stop Landing
(7) Identification of the Type of Mission that was flown.

Therefore, in this utilization concept, the onboard microprocessor does no crack growth analysis; rather it provides data to the ground based computer system where the crack growth tracking and Force Management data processing functions are carried out.

Input Parameter System Concepts

The determination of the input parameter set is fully dependent on the nature of the IAT program. In the case of the C-141, the decision was made to use an indirect parametric analysis based on the supposition that a set of 45 missions will accurately describe the full range of aircraft usage for the crack growth analysis [27]. Therefore, for the basic IAT program the only usage parameter required is the identification of the mission type. Secondary

input parameters would be flight hours per each mission flown, cumulative number of landings (by type if need be), and a flight severity index. These secondary parameters may be used to define mission variants to the 45 basic mission types or to adjust the incremental crack growth.

The basic factors which seem to have the greatest influence in determining the nature of the IAT input parameter system are:

(1) The amount of usage data detail required for the desired accuracy
(2) The limitations imposed by the IAT input parameter data acquisition system, and
(3) The complexity of the IAT cumulative crack growth analysis due to the scope and nature of the damage tolerance problem for the aircraft type under consideration.

The complexity factor is usually investigated during the preliminary phase of the development of the DADTA. The choice of DADTA methodology is beyond the scope of this study but it can be stated that one of more important driving factors is the criticality of the damage tolerance life for the aircraft. The more critical the problem, the more complex the analysis. The other factors stated above are in part also shaped by the criticality factor. The amount of usage data detail is determined by the degree of analytic detail economically justifiable and the amount of effort (in terms of cost of instrumentation, manpower, etc.) needed to define the usage of the individual aircraft.

For the C-141A transport case, a comparative crack growth analysis indicated that a parametric analysis is sufficiently accurate and therefore economically justified. It was then determined that the catagorizing of any individual usage flight into one of 45 mission types would result in a sufficiently accurate IAT analysis. Therefore, the only key IAT input parameter is the mission type identification.

The secondary parameters, such as T.O.G.W., mission duration, etc., can be used to increase the accuracy of the IAT parametric analysis by permitting the identification of usage missions which are either different from, or variations of, any of the 45 basic mission type profiles. In general, the secondary output parameters can be used in two ways. First a variant mission

type can be defined in accordance with the parameter of interest, e.g., spectrum severity or number of landings or flight duration. This method merely expands the set of defined mission types. The second method would be to adjust the crack growth for any mission type on the basis of the calculated effect of the secondary parameter. For example, if for a certain type of mission, it was determined that the spectrum severity was great, then the crack growth for the flight would be adjusted upwards. The relationship between spectrum severity and the percentage change in damage would have to be predetermined by analysis and/or test.

Another typical problem which can be handled by the above procedure is the flight time discrepancy problem. All the standard mission types have an associated specific flight duration. However the actual usage flight time (as reported via the usage logs) can vary considerably from the standard flight time. A sampling of flight time data for the three C-141 aircraft is shown in Reference 27, and reproduced here in Table 14 and in Figure 27. The data indicate that the actual usage flight time can be over 91% less or 100% more than the nominal (standard) mission duration. The impact of this variation in mission duration can not be evaluated here. However, if this flight time difference is important, as it most likely is, it is possible to adjust the incremental crack growth by introducing an adjusting factor.

The adjusting factor must be precalculated for the secondary parameter of interest, and it can be expressed in terms of the parametric crack growth variable for each mission type. In Figure 28, the value of the factor to be applied to the damage calculated for the individual flight is shown schematically.

An alternate method would be to incorporate the effect of the parameter variability, indicated by the secondary parameter, into the basic parametric analysis. This method is explained in Reference 27. For example, the effect of variable gust severity can be accounted for in the generation of the parametric damage rate by calculating the damage using a stress spectrum built up from a number of mission (or segments) spectra which incorporate a variety of gust severity spectra in a realistic ratio. The source of severity data would necessarily be L/ESS type data which were previously recorded for the aircraft or for a similar type of aircraft. The basic disadvantage of this method is

TABLE 14. DEVIATION OF C-141 AIRCRAFT RECORDED FLIGHT TIMES FROM THE BASELINE MISSION TYPE PROFILE FLIGHT TIME IN TERMS OF PERCENTAGE FOR FIVE DIFFERENT MISSION TYPES

Mission Type	4	11	22	25	31
Number of Flights in Sample Record	27	48	80	46	20
Maximum Positive Flight Time Duration	12.5	145.8	204.2	111.8	163.2
RMS Average Flight Time Duration	6.3	41.7	60.1	71.1	85.5
Positive Flight Time Deviation Average	5.4	23.3	38.9	68.9	78.5
Negative Flight Time Deviation Average	-5.3	-39.2	-54.8	0.0	0.0
Maximum Negative Flight Time Deviation	-12.5	-91.7	-86.2	0.0	0.0

Notes: 1 Data Developed from Reference 27.

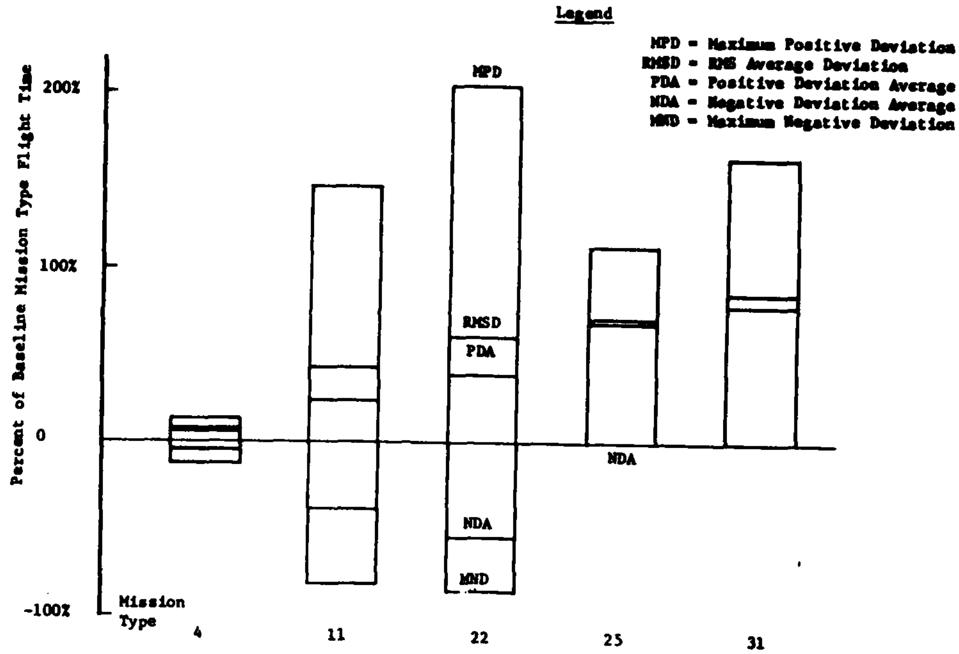
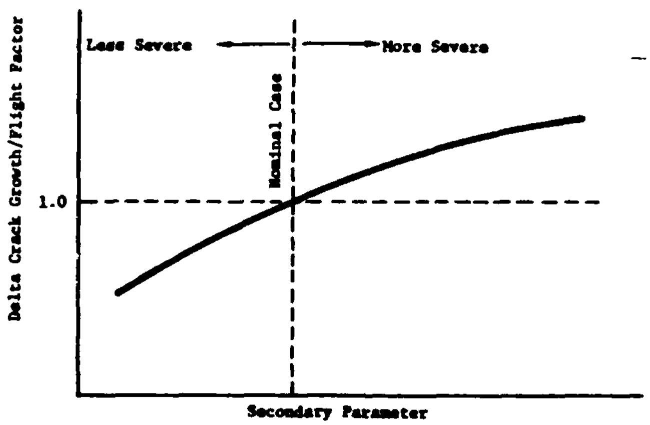


Figure 27. Deviation of Recorded Flight Times in Terms of Percentage from Baseline Mission Type Profile Flight Times for Five Missions (Reference 27)



Alternate Possibilities: Spectum Severity Parameter; Actual Flight Time Parameter; Number of Landings Parameter

Figure 28. Correction Factor (For Crack Growth Per Flight) versus Secondary Parameters used to Measure the Severity of the Flight

that it can not respond to changes in the aircraft's usage as the change occurs, because the effect of the spectrum severity is "built-in" to the damage rate parameter. Additional more up-to-date L/ESS data would be required to modify the damage rates per mission type and gust severity.

Input System Hardware/Software Factors

To replace and automate the usage form preparation function, the microprocessor must receive data from a number of sensors and/or transducers. These data are then processed by the internal software of the microprocessor in a manner similar to that in use for reducing the manually prepared usage form data.

Two different general procedures are possible: (1) mimic the current fracture tracking program logic using only those parameters specified by the usage form, and (2) use a different logic scheme based on the mission profiles to identify and quantify the mission segments. It follows then, that the selection of the crack growth rate will be either on a mission type basis or a segment type basis. Only the first method will be outlined here.

In Table 15, the minimum required μP input (activity, event, or flight) parameters have been listed for the hypothetical C-141 transport case reviewed in this report.

To describe the input parameter selection process, the initial conditions for this problem must be known. The contractor, as a result of his durability and damage tolerant analysis and IAT planning, has defined the nature of the IAT Program. In this case, the crack growth program can be catagorized as an indirect parametric analysis; that is, crack growth is solely a function of the mission type. The only requirement of the IAT input parameter system is to identify the mission type. To do so, ten different activity, event, and flight parameters must be sensed or measured (Table 15). Most of these parameters are activities which are made up of a series of pilot induced maneuvers over a period of time; for example, the stop-and-go (SAG) landing event. If the mission profile method were used, the SAG landing would be decomposed into a number of mission segments such as traffic pattern descent, landing and roll-out, post-landing ground, ground roll and take-off, climb, and traffic pattern.

TABLE 15. MISSION PARAMETERS REQUIRED TO DETERMINE TYPE OF MISSION PER LOCKHEED-GEORGIA CO. DECISION LOGIC TREE DIAGRAM.

MISSION TYPE	DECISION TREE PARAMETERS REQUIRED TO DEFINE MISSION TYPE									
	EVENT PARAMETERS						FLIGHT PARAMETERS			
	AIRDROP	TAG	SAG	CONTOUR FLYING AND DURATION	CRUISE AND DURATION	MISSION DURATION	ALTITUDE	MACH NUMBER	FUEL WEIGHT	CARGO WEIGHT
MEDIUM RANGE LOGISTICS WITH MEDIUM CARGO WEIGHT PROFILES 1 THRU 4		R	R			R				R
MEDIUM RANGE LOGISTICS WITH HIGH CARGO WEIGHTS PROFILES 5, 6, 7		R	R			R				R
SHORT RANGE LOGISTICS WITH LOW CARGO WEIGHTS PROFILES 8, 9, 10		R	R		R	R	R		R	R
SHORT RANGE LOGISTICS WITH MEDIUM CARGO WEIGHTS PROFILES 11, 12, 13		R	R		R	R	R		R	R
SHORT RANGE LOGISTICS WITH HIGH CARGO WEIGHTS PROFILES 14, 15, 16		R	R		R	R	R		R	R
SHORT RANGE LOGISTICS WITH HEAVY FUEL LOAD PROFILES 17, 18, 19		R	R		R	R	R		R	R
LONG RANGE LOGISTICS PROFILES 20, 21		R	R			R				R
SPECIAL LOGISTICS PROFILE 22		R	R		R	R	R		R	R
TRAINING/NO AIRDROP PROFILES 23 THRU 32	R	R	R							R
TRAINING/WITH AIRDROP PROFILES 33, 34	R	R	R	R	R		R	R		
TRAINING/WITH AIRCROP LOW ALTITUDE/DURATION 30 MIN. PROFILES 35, 36, 37	R	R	R	R	R	R	R	R		

	AIRDROP	TAG	SAG	AND DURATION	AND DURATION	MISSION DURATION	ALTITUDE	MACH NUMBER	FUEL WEIGHT	CARGO WEIGHT
MEDIUM RANGE LOGISTICS WITH MEDIUM CARGO WEIGHT PROFILES 1 THRU 4		R	R			R				R
MEDIUM RANGE LOGISTICS WITH HIGH CARGO WEIGHTS PROFILES 5, 6, 7		R	R			R				R
SHORT RANGE LOGISTICS WITH LOW CARGO WEIGHTS PROFILES 8, 9, 10		R	R		R	R	R		R	R
SHORT RANGE LOGISTICS WITH MEDIUM CARGO WEIGHTS PROFILES 11, 12, 13		R	R		R	R	R		R	R
SHORT RANGE LOGISTICS WITH HIGH CARGO WEIGHTS PROFILES 14, 15, 16		R	R		R	R	R		R	R
SHORT RANGE LOGISTICS WITH HEAVY FUEL LOAD PROFILES 17, 18, 19		R	R		R	R	R		R	R
LONG RANGE LOGISTICS PROFILES 20, 21		R	R			R				R
SPECIAL LOGISTICS PROFILE 22		R	R		R	R	R		R	R
TRAINING/NO AIRDROP PROFILES 23 THRU 32	R	R	R							R
TRAINING/WITH AIRDROP PROFILES 33, 34	R	R	R	R	R		R	R		
TRAINING/WITH AIRCROP LOW ALTITUDE/DURATION 30 MIN. PROFILES 35, 36, 37	R	R	R	R	R	R	R	R		
TRAINING/WITH AIRDROP LOW ALTITUDE/DURATION 30 MIN. PROFILES 38, 39, 40	R	R	R	R	R	R	R	R		
LOW LEVEL NAVIGATION PROFILES 41, 42	R	R	R	R	R	R	R		R	R
LOW LEVEL NAVIGATION WITH CONTOUR FLYING PROFILES 43, 44	R	R	R	R	R	R	R		R	R
FLIGHT TEST/PROFILE 45		R	R		R	R	R		R	R

Notes: 1. Configuration parameters are not required by the decision logic because they are assumed constant for specific mission segments within the mission type profile.

2. Event parameters mark the occurance of a specific event and in some cases the duration of that event.

3. R = Required

Three of the parameters required to determine the mission type are not events or activities in the above sense. These three (cargo weight, fuel weight, and mach number), can be better described as flight parameters. The approach used to fully define the IAT input parameter system both in terms of logic and hardware is shown in Figure 29.

In the case under study, the identities of the 45 selected mission type profiles are the only inputs required to calculate the incremental parametric crack growth. A decision logic tree diagram is used to determine the logical events needed to identify each of the 45 mission type profiles. The next step is to examine each logical event to select whatever aircraft activity or response parameters are needed to reliably determine that the logical event has occurred and how often it has occurred. For example, the detection of stop-and-go (SAG) landings is necessary to determine the mission type. In order to detect the occurrence of the SAG landing, eight input parameters were determined as useful. Of the eight input parameters, four or five may be considered to be redundant and not economically justified. The primary input parameter would be the weight-on-landing gear signal. However, by itself, this parameter can not distinguish between touch-and-go (TAG) landings and (SAG) landings. One or more additional input parameters must be used to differentiate between TAG and SAG landings. Since a SAG landing results in the aircraft remaining on the ground for a longer period of time than is usual for TAG landings, the time parameter in combination with the weight-on-landing gear signal may be used to distinguish between them. However, a more reliable input parameter is the airspeed since a SAG landing will result in the airspeed falling to zero while the aircraft doing a TAG landing should not lose its forward velocity. The other listed input parameters are redundant, but they can provide data to verify the primary logical event. The most economical selection of input parameters would be (1) weight-on-landing gear signal, (2) time signal, and (3) the airspeed signal.

The next step, as indicated in Table 16, is to determine, from the nature of the input parameters, the hardware required to sense, measure or record the input parameters. In the above example, the three suggested input parameters will require (1) an electro-mechanical position sensor for the landing gear, (2) a clock which is an integral part of the μP, and (3) airspeed instrumentation.

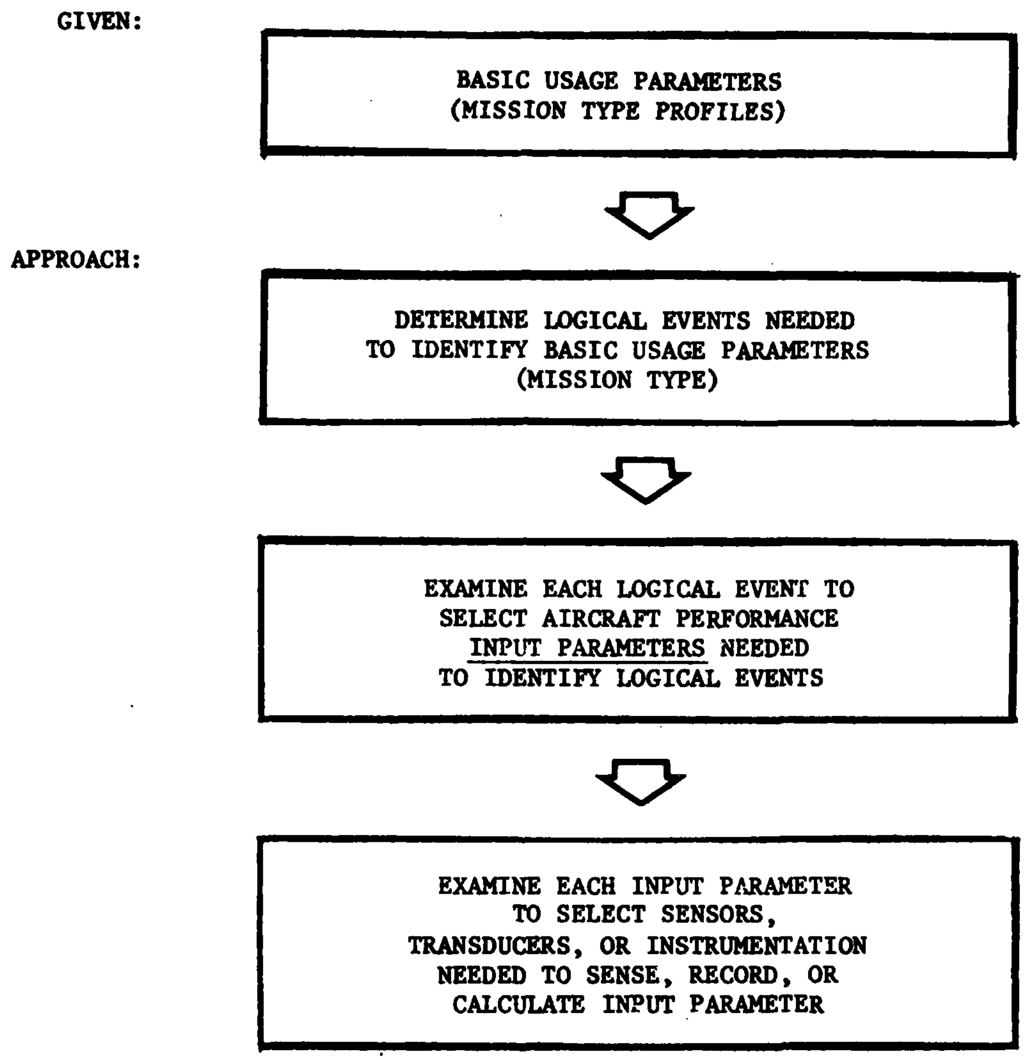


Figure 29. Method Used to Analyze and Plan IAT Input Parameter System for a Parametric Type of Program

Selection of Logical Events

In this case where the mission type is the key usage parameter, the only method for selection of the defining logical events is to review all of the mission type profiles and to choose those events or sets of events which unambiguously define a specific mission type. Given the nature of military cargo transports and their missions, the selection of those logical events shown in the first row of Table 16 is not suprising. It is recommended and probably necessary that a decision logic tree diagram be constructed to show the relationship among the various logical events and how a mission type can be identified. The full 45 mission type decision logic tree diagram has not been reproduced here, but a section of it, needed to identify ten different training missions, has been diagrammed in Figure 30.

The only general rule which can be established is that each logical event is either (1) made up of one or more mission segments which define a tactical maneuver or activity, or (2) made up of qualifying parameters which modify the definition of the mission type. For example, a stop-and-go landing is made up of a series of well defined mission segments, which together make up the SAG tactical maneuver. In addition, the cargo weight parameter is a significant indicator used to create a subset of SAG landings or mission types where the structural damage is largely a function of the aircraft's weight, as in Figure 31.

The listed set of logical events/activities (Table 16) and the input parameters (second row) are not intended to be considered as final since they would vary according to the nature of the aircraft and its anticipated composite mission history. For example, the transport's cargo weight and cargo airdrop logical event categories would be replaced by weapons weight and weapons delivery logical event categories for the case of a bomber.

Microprocessor Logic for the Input Parameter System

The μP operates on two levels - real time and non-real time. During the flight in the real time operating mode, the μP receives processed digitized signals from the sensors and other instrumentation and determines if a pre-defined logical event has occurred. Knowledge of the occurrence of any of

TABLE 16. CONCEPTUAL IAT MICROPROCESSOR INPUT PARAMETER ARRAY FOR LARGE AIRCRAFT CLASS USING A PARAMETRIC TYPE OF CRACK GROWTH PROGRAM

LOGICAL EVENTS/ ACTIVITIES	CRUISE AT SELECTED ALTITUDE BANDS AND DURATION	DURATION OF MISSION	CARGO WEIGHT	FUEL WEIGHT	MACH NUMBER
INPUT PARAMETERS REQUIRED TO DETERMINE LOGICAL EVENT/ACTIVITY	ALTITUDE AIRSPEED NORMAL VERTICAL ACCELERATION (N_z)	TIME SIGNAL ENGINE START/STOP WEIGHT ON LANDING GEAR SIGNAL	DATA KEY BOARD INPUT	DATA KEY BOARD INPUT TOTAL FUEL FLOW	MACH NUMBER
SENSORS, TRANSDUCERS, AND INSTRUMENTATION REQUIRED TO SENSE, MEASURE OR RECORD INPUT PARAMETERS	ALTIMETER	ALTIMETER			
	AIRSPEED INSTRUMENTATION				AIRSPEED INSTRUMENTATION
		ELECTRO-MECHANICAL POSITION SENSOR (2 REQUIRED)			
	LINEAR VERTICAL ACCELEROMETER				
	RATE OF CLIMB INSTRUMENTATION				
	MICROPROCESSOR CLOCK	MICROPROCESSOR CLOCK			
			DIGITAL ALPHA-NUMERIC KEYBOARD	DIGITAL ALPHA-NUMERIC KEYBOARD	
				FUEL FLOW TRANSDUCER	

TABLE 16. CONCEPTUAL IAT MICROPROCESSOR INPUT PARAMETER ARRAY FOR THE LARGE AIRCRAFT CLASS USING A PARAMETRIC TYPE OF CRACK GROWTH PROGRAM (CONCLUDED)

LOGICAL EVENTS/ ACTIVITIES	AIRDROP OF CARGO	TOUCH-AND-GO LANDING	STOP-AND-GO LANDING	CONTOUR FLYING AND DURATION
INPUT PARAMETERS REQUIRED TO DETERMINE LOGICAL EVENT	ALTITUDE AIRSPEED CARGO DOOR OPEN/CLOSE SIGNAL DATA KEY BOARD INPUT	WEIGHT ON LANDING GEAR SIGNAL AIRSPEED RATE OF CLIMB/ DESCENT ENGINE START/ STOP SIGNAL ENGINE POWER SIGNAL	WEIGHT ON LANDING GEAR SIGNAL AIRSPEED RATE OF CLIMB/ DESCENT ENGINE START/ STOP SIGNAL ENGINE POWER SIGNAL THRUST REVERSE SIGNAL BRAKE APPLICATION SIGNAL TIME SIGNAL	ALTITUDE AIRSPEED NORMAL VERTICAL ACCELERATION (N_z) TIME SIGNAL
SENSORS, TRANSDUCERS, AND INSTRUMENTATION REQUIRED TO SENSE, MEASURE OR RECORD INPUT PARAMETERS	ALTIMETER			ALTIMETER
	AIRSPEED INSTRUMENTATION	AIRSPEED INSTRUMENTATION	AIRSPEED INSTRUMENTATION	AIRSPEED INSTRUMENTATION
	ELECTRO-MECHANICAL POSITION SENSOR	ELECTRO-MECHANICAL POSITION SENSOR	ELECTRO-MECHANICAL POSITION SENSOR (3 REQUIRED)	
		ENGINE POWER INSTRUMENTATION	ENGINE POWER INSTRUMENTATION	LINEAR VERTICAL ACCELEROMETER
		RATE OF CLIMB INSTRUMENTATION	RATE OF CLIMB INSTRUMENTATION	
			MICROPROCESSOR CLOCK	
	DIGITAL ALPHA-NUMERIC KEYBOARD			

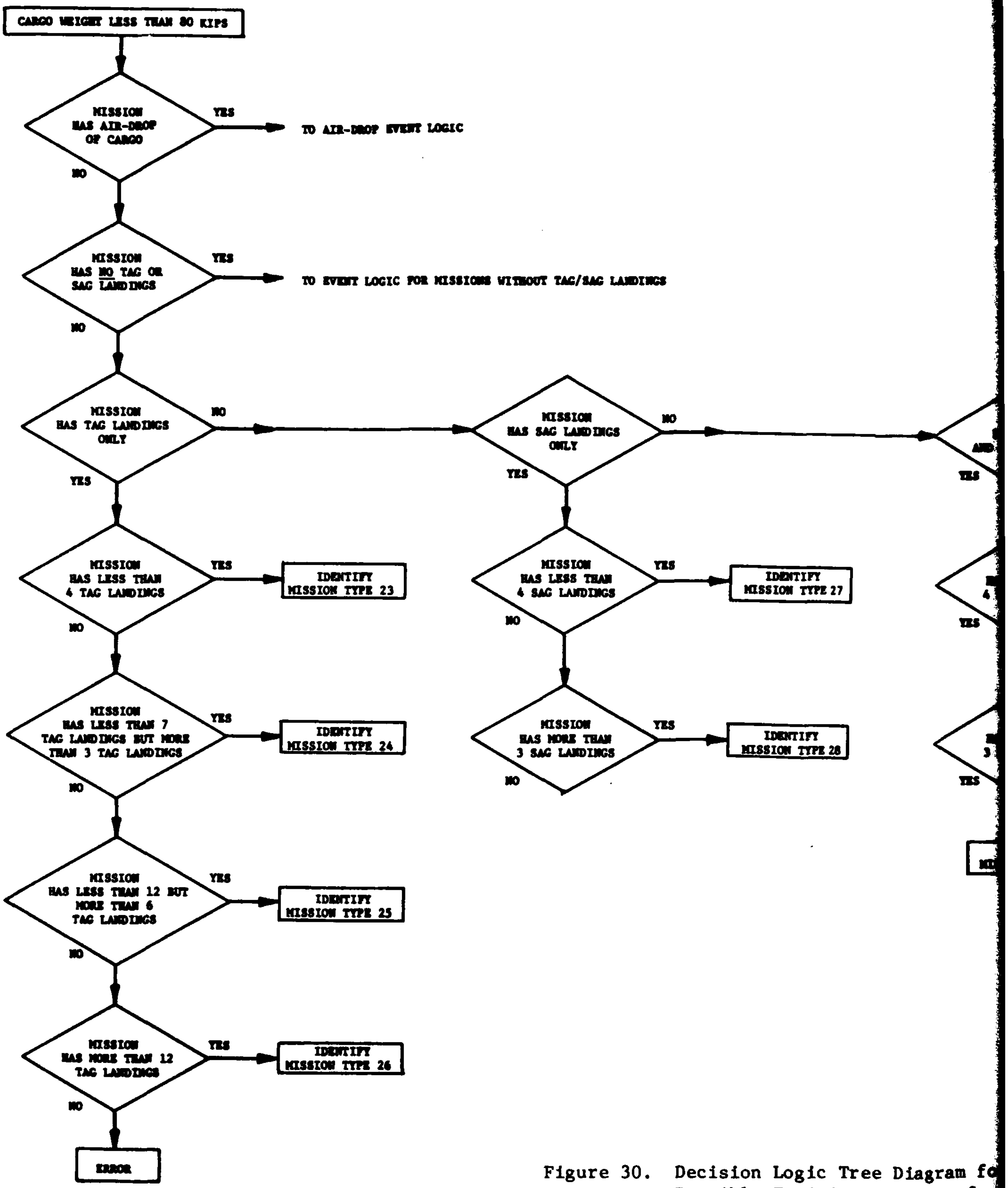
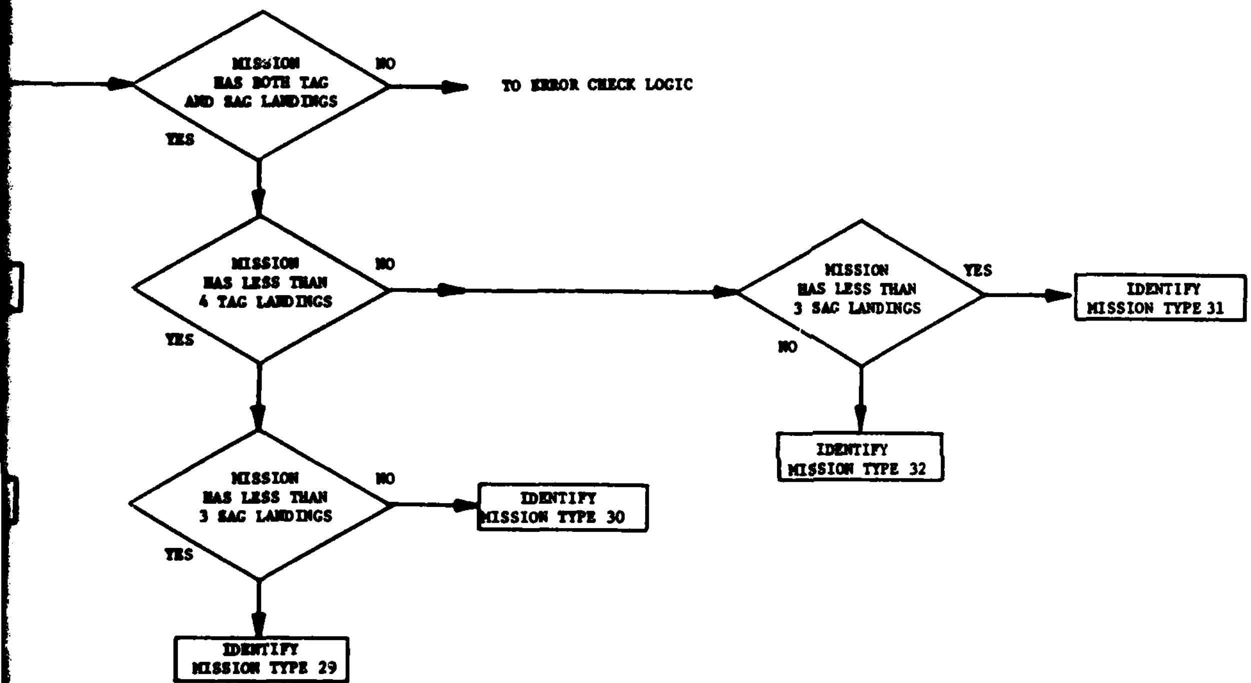


Figure 30. Decision Logic Tree Diagram fo
Possible Training Missions fo



ree Diagram for Classification of Ten
Missions for the C-141 IAT Program

1 2

the logical events (as defined in Table 16) is stored for later processing at the end of the flight or after the start of the next flight. By the end of the flight, the μP will have processed all of the sensor signals and stored all of the logical event occurrences needed to define a mission type. At this point, the μP processes (in a non-real time mode) the stored logical event data to determine the identity of the mission type. This activity parameter is then stored along with other data such as the aircraft's serial number, cumulative flying hours, etc.

A typical example of the real time processing of the input parameters is illustrated in Figure 32. This flow chart shows the system logic used for the various types of landings. To a large extent the choice of input parameters and their utilization is arbitrary because there are several different logical ways of reaching the same decision. The input parameters used here are airspeed, weight-on landing gear signal, clock time, engine on/off signal, brake application signal, and engine power signal. The minimum input parameters are the first three and the others are redundant but may be useful in adding to the reliability of the system. In this example, the most difficult logic problem is to distinguish between a TAG and a SAG landing. This is done by assuming that the SAG landing will activate the weight-on-landing gear signal for a much longer period of time than a TAG landing would. Therefore, the weight-on-landing gear signal is timed, and if its duration is greater than some minimum time period, then the landing is assumed to be a SAG or a final landing. Alternately, other input parameters such as the brake application signal or an engine thrust reverser signal could be used to supplement or replace some of the other input parameters. The use of these parameters assumes that brakes and thrust reversers are never (or not usually) used for TAG landings.

The data which are output by this input parameter processing program are not the IAT output parameters. Rather, these data are intermediate parameters which will be input to the mission type identification program which is a subroutine of the IAT program residing in the onboard microprocessor. A logic tree diagram of such a subroutine is shown in Figure 15 for the C-5A craft and is in essence an extension of Figure 32. The mission type identification subroutine uses the end-of-the flight intermediate parameters to logically identify the mission type. These parameters are grouped into three categories:

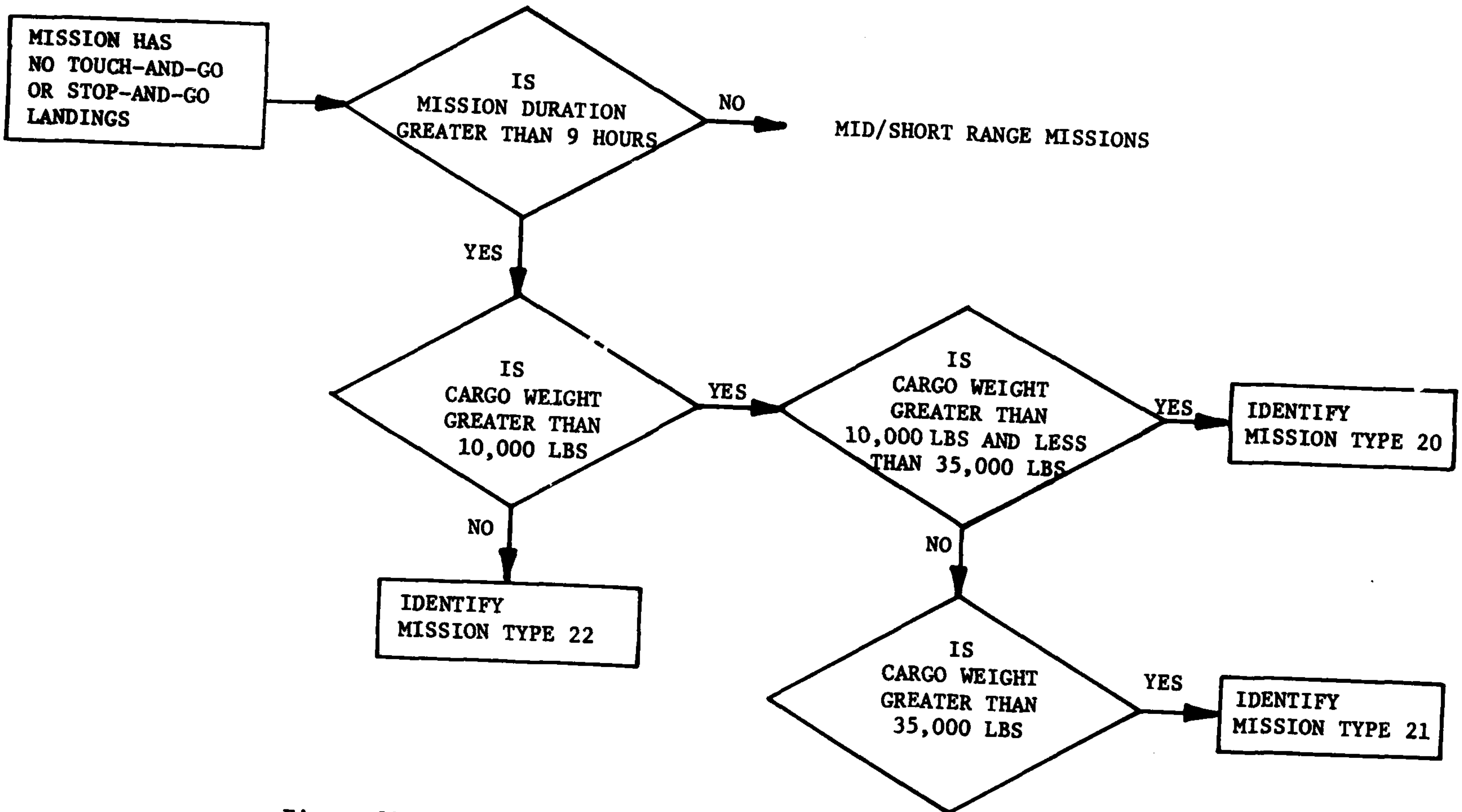
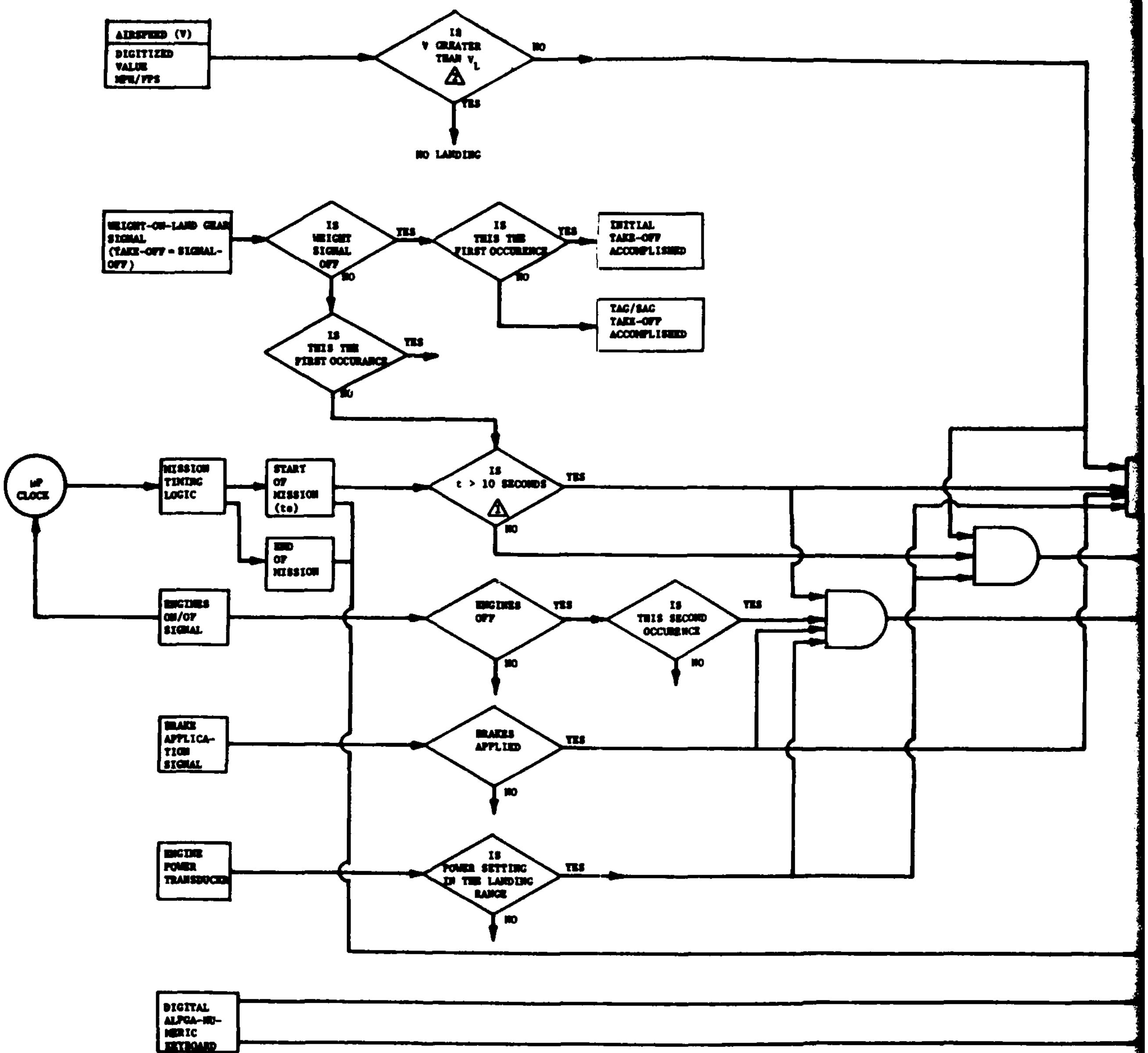


Figure 31. Decision Logic for Classification of Long Range Logistics Mission Types for C-141 Transport (Reference 27)



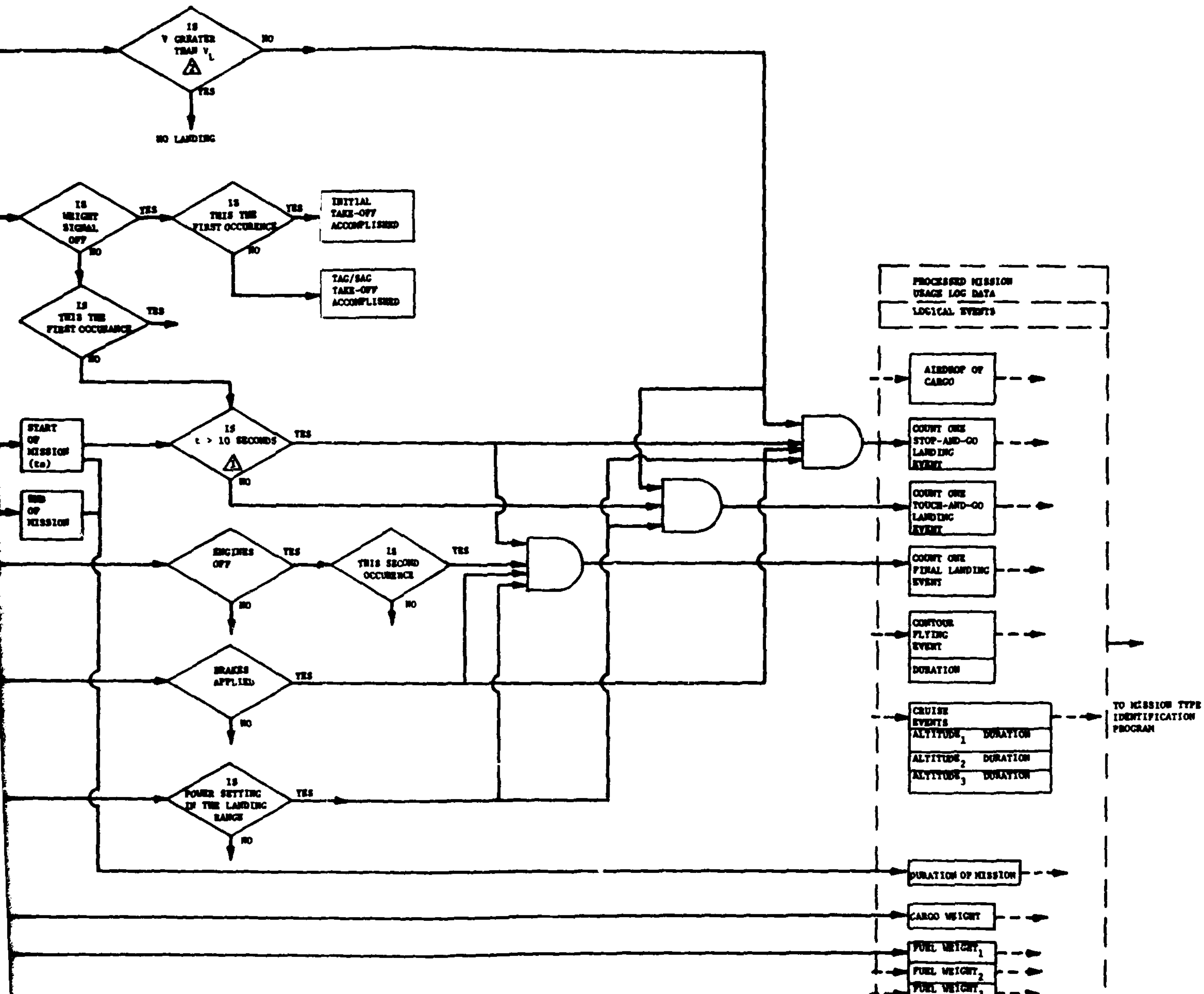
Notes: 1. A time greater than 10 seconds indicates that the aircraft has been on the ground long enough to define a SAC or Final Landing. The 10 second parameter is arbitrary and is not to be considered a real case value.

2. V_L is the maximum landing speed

3. Landing event data is stored for processing at end of flight when the μP program will process all new flight data to identify the mission type flown.

4. For clarity and simplici.y, those flow arrows not leading to essential parts of the logic network are not continued.

Figure 32. Real-Time Microprocessor System Logic for Identifying, Touch-and-Go, Stop-and-Go, and Final Landing Occurrenc
Processing via the Mission Type Identification Program



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y and is not to be considered a real case value.

he maximum landing speed

event data is stored for processing at end of flight when the uP program
cess all new flight data to identify the mission type flown.

ity and simplicity, those flow arrows not leading to essential parts of the
twork are not continued.

Figure 32. Real-Time Microprocessor System Logic for Identifying, Counting, and Storing Touch-and-Go, Stop-and-Go, and Final Landing Occurrence Data for further Processing via the Mission Type Identification Program

/ 2

(1) activity parameters such as a contour flying and cruise flying, 2) event parameters such as the occurrences of airdrops of cargo, touch-and-go landings, stop-and-go landings, final landings, and mission duration, and (3) flight parameters such as a maximum altitude, maximum airspeed or Mach number, fuel weight at take-off and landing, and cargo weight. The output of the mission identification subroutine is, of course, the identification code for the mission type just flown.

A sample of program statements used in such a subroutine is shown in Figure 33. This set of statements is based on the decision tree diagram shown in Figure 30, whose purpose is to identify one of ten possible training mission types usually flown in the C-141A transport. This subroutine uses only one flight parameter (cargo weight) and three event parameters (occurrences of cargo airdrops, touch-and-go landings, and stop-and-go-landings) to identify eight different mission types which differ predominately in the number of TAG and SAG landings.

Alternate Concepts

The major tasks of the total IAT system are outlined in Figure 34. If tasks 1, 2, and 3 are to be performed by the onboard IAT μP, then it is in essence an electronic method of producing a flight log. The remainder of the IAT effort would be performed on a ground based main frame computer as it is now being done in the C-5A program. For first generation systems which are handicapped by moderate amounts of μP system memory, there is no other choice. Data were not available to evaluate the feasibility of performing all parts of the IAT program onboard the aircraft for smaller transports like the CT-39. However, since the existing CT-39 IAT program is considerably smaller than the C-5A or the C-141 programs, there is a strong possibility that it may be possible to run the complete program onboard the aircraft's μP system.

The decision as to whether the μP system will function as a data acquisition device (that is, a flight log) or as a complete data acquisition and analysis system depends on the amount of μP system memory required.

1	If cargo weight is less than 80,000 branch to 10
2	Branch to 4000
10	If Airdrop flag indicates occurrence branch to 4000
20	If TAG and SAG landing counters indicate no TAG/SAG landings branch to 4000
21	If both TAG and SAG landing counters indicate more than 0 occurrences branch to 300
22	If TAG landing counter indicates occurrences greater than 0 branch to 200
23	If SAG landing counter indicates occurrences less than 4 branch to 30
24	Count an occurrence of Mission Type 27
25	Branch to 1000
30	Count an occurrence Mission Type 28
31	Branch to 1000
200	If TAG landing counter indicates occurrences less than 4 branch to 250
201	If TAG landing counter indicates occurrences less than 7 branch to 260
202	If TAG landing counter indicates occurrences less than 12 branch to 270
203	Count an occurrence of Mission Type 26
204	Branch to 1000
250	Count an occurrence of Mission Type 23
251	Branch to 1000
260	Count an occurrence of Mission Type 24
261	Branch to 1000
270	Count an occurrence of Mission Type 24
271	Branch to 1000
300	If TAG landing counter indicates occurrences less than 4 branch to 310
301	If SAG landing counter indicates occurrences less than 3 branch to 330
302	Branch to 340
311	Count an occurrence of Mission Type 30
312	Branch to 1000
320	Count an occurrence of Mission Type 30
330	Count an occurrence of Mission Type 31
331	Branch to 1000
340	Count an occurrence of Mission Type 32
341	Branch to 1000
1000	Store flight sequence number
1001	Store calendar date
1002	Store calendar time (Zulu)
4000	(Other subroutine of program)

Figure 33. Sample of Software Statements Used to Identify Parametric Mission Types (Limited to Training Mission)

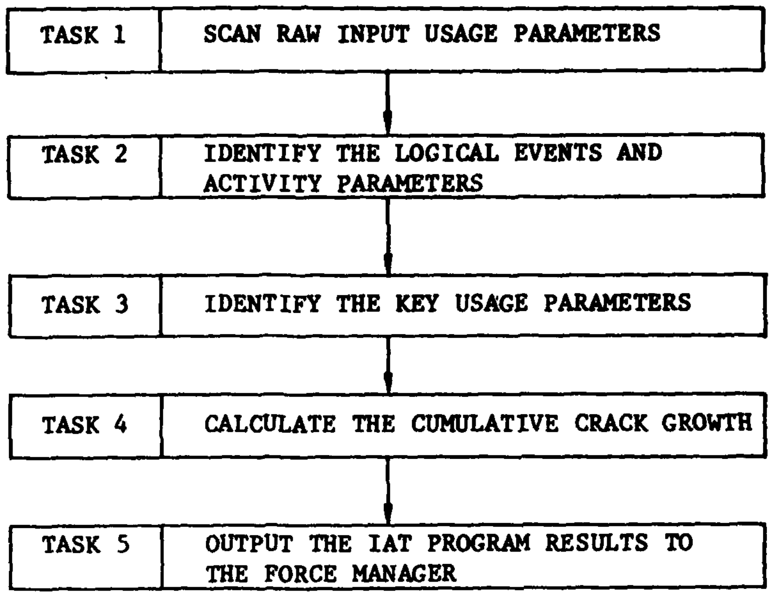

Figure 34. Outline of the Major Tasks or Subroutines Within the IAT Computer Program

5. Definition of Output Parameter Requirements

The IAT output parameters are those parameters which predict the durability and/or damage tolerance status of the structure and enable the force manager to modify and/or implement the Force Structural Maintenace Plan. The basic measure of the structure's status is the current predicted length of an assumed pre-existing initial flaw. This predicted crack length is determined by a cumulative crack growth analysis using the aircraft's monitored history to analytically generate the crack's growth. IAT analyses can usually provide the following output parameters:

(1) The current predicted crack length based on an assumed initial manufacturing flaw of a size normally used in damage tolerance analysis.

(2) The current predicted crack length based on an assumed very small non-inspectable crack normally used in durability-economic life analysis.

(3) The current predicted crack length based on an initial flaw size assumed to exist as a result of an inspection.

(4) The normalized crack length in terms of a Damage Index (DI)

(5) A spectrum severity parameter in the form of the current crack growth rate (da/dt) which is calculated by applying the current load spectrum for a fixed duration of flight time (several hundred hours) to a fixed initial crack length.

To do the durability and damage tolerance analysis, a planned or anticipated force service history is developed and used to predict the anticipated crack growth behavior for the nominal force aircraft. This is the standard against which all actual individual aircraft crack growth behavior are compared.

Minimum Set of Required IAT Output Parameters

The minimum set of IAT output parameters is shown in Table 17. It is made up of (1) documentation (or identification) data, and (2) the cumulative crack growth analysis output data for each structural control point.

TABLE 17. RECOMMENDED MINIMUM SET OF IAT OUTPUT PARAMETERS

Individual Aircraft Data Base
A. Documentation (ID) data 1. Aircraft serial number (USAF/Manufacturer) 2. Aircraft's owning unit Command Wing Group Squadron 3. Home base 4. Current cumulative logged flying time on aircraft 5. Current mission (sortie) count 6. Date of last tracking report 7. Date of last force management analysis 8. Number and identity of all structural control points
B. IAT Output Data Base Per Control Point
9. Remaining and predicted durability life 10 Current crack length for all types of tracked cracks 1. Durability crack 2. Damage tolerance crack 3. Inspection crack 11. Current damage index (if used) 12. For last reporting period 1. Crack growth 2. Crack growth rate 3. Damage index rate 13. Cumulative number of landings (all types) 14. Cumulative number of high damaging events (IFR, cargo drop, etc.)
Aircraft Component Tracking
A. Documentation (ID) data same as above B. IAT output data base per control point on component Same as above

6. Specification of IAT Input Parameter Requirements

Identifying the Input Parameters

The major factors affecting the selection of input parameters are:

(1) The complexity of the aircraft's various aerodynamic configurations

(2) The varieties of the forces's planned or potential mission profiles and lifetime mission mixes.

(3) The variety of planned and possible loading conditions (points-in-the sky) for the aircraft.

(4) The type of IAT analysis developed for the aircraft.

This assertion is supported by the data presented in Therefore, it is concluded that a defined set of required input parameters can not be specified beforehand for any type of aircraft.

Table 18 lists the more commonly used first level input parameters subcatagorized by type as previously defined in Section III. It is acknowledged that there exists a degree of arbitrariness as to whether certain parameters may be listed as configurational or flight parameters. In this report, configurational parameters are those which can be (and usually are) sensed by instruments, while flight parameters usually can not be economically or practically sensed by instruments.

Documentation of Aircraft/Aircraft Component Identification Parameters

Data Items

For all IAT Systems a set of individual aircraft identification or documentation parameters are required both as IAT input and output parameters. The minimum data required are:

(1) Aircraft serial number (USAF)

(2) Manufacturer's serial number for the aircraft

(3) Aircraft's owning unit by command, wing, group, and squadron

(4) Home base

(5) Current cumulative flying time logged on the aircraft

TABLE 18. COMMON INPUT PARAMETERS

RESPONSE PARAMETERS	CONFIGURATION PARAMETERS	FLIGHT PARAMETERS
Mach Number or True Airspeed	Wing Position (If Variable)	Gross Take-Off Weight
Altitude	Nozzle Position (If Variable)	Cargo Weight
Sink Speed	Flap Position	Fuel Quantity
Normal Linear Acceleration	Aileron Position	Mission Type
Lateral Linear Acceleration	Canard Position	Gun Firing and
Longitudinal Linear Acceleration	(Both if Differential)	Ammunition Weight
Pitch Acceleration	Horizontal Tail Position	Store Inventory
Yaw Acceleration	(Both if Differential)	Air Cargo Drop
Roll Acceleration	Rudder Position	
Pitch Rate	Speed Brake Position	
Yaw Rate	Store Inventory	
Roll Rate	Fuel Quantity	
Pitch Attitude	Landing Gear Position	
Roll Attitude		
Yaw Angle		
Angle-of-Attack		
Fight Path Angle		
Strain		
Time		

(6) Current mission (sortie) count

(7) Date and Zulu time for the mission

(8) Date of data retrieval from the aircraft

For those aircraft which have interchangeable major components such as left and right hand horizontal stabilizers and wing panels and for those aircraft which have a critical fatigue problem on a major component, it becomes important to include identification parameters for those major components.

(9) Manufacturer's serial numbers for all major aircraft components of interest

(10) Current cumulative flying time logged on the above major components

For those IAT programs which use the onboard μP to calculate the cumulative crack growth a number of analytic parameters must be input and carried as part of the documentation parameter set. These data items are:

(11) Nomenclature for the control points being analyzed

(12) Initial crack length for each control point and for each type of crack or flaw being tracked.

Methods of Inputting the Documentation Parameters

There are only two methods of loading the documentation parameters into the μP system memory.

(1) Use the alphanumeric keyboard or an annunciator panel to manually key in the data.

(2) Use the portable ground data retrieval unit to electronically load the data into the onboard μP system.

Some of the documentation parameters can only be input by means of a keyboard permanently installed in the aircraft. The use of the portable ground data retrieval unit is too difficult and time consuming to use it prior to each flight. It would normally be used at the beginning of the program when the IAT μP system is initially started and only intermittantly to modify the documentation parameters or to retrieve the processed operational IAT data.

Configuration/Flight Parameters

If the aircraft IAT program is similar to the C-5A program where configuration and flight parameters must be manually input because of lack of sensor or instrument input, the following parameters must be input for each flight by means of the alphanumeric keyboard.

(1) Cargo weight
(2) Fuel weight at take-off
(3) Take-off gross weight
(4) Special events
    a) Cargo airdrops
    b) Cargo jettison
(5) Type of mission to be flown based on a set of standard mission definitions.

7. Force Management Data Concepts

Advantages of a Microprocessor-Based IAT System

In terms of Force Management, the chief advantages of a highly automated microprocessor-based IAT system are

(1) A major reduction in the time lag between IAT data acquisition and IAT data output,
(2) A major improvement in the accuracy, scope, and reliability of the IAT output data.
(3) A significant reduction in manual processing (all types) of the IAT data.

The degree to which the above advantages are realized depends on the degree to which the total IAT and FM system is automated.

Basic Functions of Force Management and How IAT Impacts FM Functions

The Force Structural Maintenance (FSM) Plan, developed as an ASIP task, is the basic tool used by the force manager. In general, the FSM plan will direct the inspection, repair, or replacement of structural components at specified time intervals or flight hour milestones. The plan also specifies

the maintenance echelon level, the procedure to be used, and the ultimate retirement milestone for the individual aircraft if the durability and/or damage toler ce life is less than the programmed service life.

The IAT program can only impact two features of the FSM plan: (1) what structural parts or areas are to be subjected to maintenance action, and (2) when (usually in terms of aircraft logged flight time) the maintenance action is to be taken.

All milestones in the original FMS plan are based on the DADTA which used an anticipated Load/Environment (L/E) history for the typical force aircraft. It is the purpose of the IAT program to identify those force aircraft which have experienced a L/E usage history significantly different from the DADTA L/E history and to enable the force manager to revise the FSM plan for those aircraft.

The force manager usually adjusts the maintenance action schedule for the individual aircraft as indicated by some measure of crack growth. In general there are two types of measures of damage: relative and absolute. The relative measure is the commonly used damage index concept while the absolute measure is the actual predicted crack length for the control point. The damage index (DI) for any control point represents the percentage of the predicted damage tolerance life that has been used up. The absolute predicted life, which was calculated in the DADTA, is normalized so that at the time of critical crack length (failure) the DI is equal to 1.0; that is 100 percent. Two options are available: (1) all control points are tracked relative to the generalized control point, or (2) all control points are independently tracked. The first option (used in the F-4 IAT program) requires that the current DI at the generalized control point be transformed to the appropriate DI values for the other control points by means of DI ratios which had been previously determined as part of the DADTA. The second option only requires that the monitored DI be corrected relative to the predicted normalized crack growth curve. Various approaches, all of which have a great deal in common, have been developed and published [6,11,18,20,32,33].

The use of the absolute crack length as a measure of damage tolerance life is the simpler approach but has the disadvantage that, as a measure of damage, it can not be directly and immediately related to damage at other locations. Therefore, all control points must be tracked.

Whatever type of IAT output parameter is used to measure the damage, the FSM plan must have the means to use the individual aircraft's damage parameter(s) to revise the maintenance action time schedules. The means to do this will necessarily be a computer program. The FM computer program will have an algorithm capable of manipulating the IAT output parameters (DI, flight hours logged, crack length, etc.) on the basis of the originally predicted crack growth history and critical crack length and then determining the maintenance action schedule for the individual aircraft.

Force Management Data Base

The FM data computer program will have two different data bases - the individual aircraft data base and the force's data base. The first pertains to all the data acquired and stored for each individual aircraft and, if needed, each individual airframe's major components. The second refers to all the statistical population data acquired for the total force. The variety of data which is possible to collect and generage is extremely numerous as can be seen to be the case with the C-5A transport (Section VI and Appendix A). The same basic data item can be presented to the force manager in numerous ways. But, because of the differences in the IAT programs for the various forces, it is difficult to develop a generalized FM data base description which would fit all types of aircraft forces.

Therefore, the basic conclusions relative to the management of the FM data base are:

(1) The C-5A FM data base system, with some revisions, should serve as an extended model from which the FM data base for other aircraft can be developed

(2) The typical aircraft force's FM data base should include as a minimum the data (or its equivalent) shown in Table 19.

TABLE 19. RECOMMENDED MINIMUM FM DATA BASE FOR THE FORCE POPULATION

SUMMARY DATA AND STATISTICS
A. Force population distributions for 1. Flight time 2. Flight time by mission type 3. Logged flight time versus planned flight time 4. Various reported usage parameters versus planned usage parameters
B. Aircraft Ranking by 5. Time to maintenance action 6. Logged flight hours 7. Damage index 8. Crack length 9. Other durability and damage tolerance parameter(s)
C. Trends of actual versus planned usage, activity and event parameters
D. Past Usage Characterizations 10. Deviation in usage parameters from various planned usage parameters
E. Durability and damage tolerance status 11. Force population distribution for a. Durability parameter(s) b. Damage tolerance parameter(s) 12. Five percent most critical aircraft 13. Five percent least critical aircraft

SECTION VIII

DEFINITION OF IAT SYSTEM HARDWARE AND SOFTWARE CAPABILITIES AND REQUIREMENTS

In this section, the hardware and software systems are described in terms of the more likely required input parameter sets for both classes of aircraft and the instrumentation normally used to sense and measure these parameters. Several important aspects of system software requirements and characteristics are also discussed.

1. Input Sensor/Transducer Capabilities and Requirements

Fighter/Attack/Trainer IAT Systems

A variety of usage parameters will be required for the loads analysis which is a prerequisite for determining the external load-to-internal load transfer functions. These transfer functions are necessary to determine the stress history for any control point. Because of the variation in aircraft usage and design, it is difficult to determine what usage parameters are necessary for a generalized case. Based on Northrop's experience and a review of the literature, a number of probable usage input parameters have been listed in Table 20. This list is not intended to be exhaustive and parameters should be added or removed as required by special design conditions.

The sensors, transducers, and instrumentation required to monitor the listed usage parameter are:

(1) Three axis linear accelerometers

(2) Three axis gyros

(3) Fuel flow transducer

(4) Position Synchro Transducers

(5) Air-Data Computer

(6) Strain Gages

TABLE 20. PROBABLE USAGE INPUT PARAMETERS FOR IAT AND LOADS ANALYSIS

TYPE OF PARAMETER	WING CONTROL POINTS	FUSELAGE CONTROL POINTS	HORIZONTAL STABILIZER CONTROL POINTS	VERTICAL STABILIZER CONTROL POINTS
AERODYNAMIC RESPONSE PARAMETERS	VERTICAL ACCELERATION AIRSPEED ALTITUDE ROLL RATE/ACCELERATION PITCH RATE/ACCELERATION YAW RATE/ACCELERATION SINK SPEED ANGLE OF ATTACK STRAIN FOR SELECTED STRUCTURE	VERTICAL ACCELERATION LATERAL ACCELERATION AIRSPEED ALTITUDE ROLL RATE/ACCELERATION YAW ANGLE/RATE/ACCELERATION PITCH RATE/ACCELERATION SINK SPEED ANGLE OF ATTACK STRAIN AT SELECTED LOCATIONS	VERTICAL ACCELERATION AIRSPEED ALTITUDE ANGLE OF ATTACK	VERTICAL ACCELERATION LATERAL ACCELERATION AIRSPEED ALTITUDE ANGLE OF ATTACK YAW ANGLE/RATE/ ACCELERATION
CONFIGURATION PARAMETERS	AILERON DEFLECTION FLAP DEFLECTION SPEED BRAKE POSITION WING SWEEP ANGLE VECTORED THRUST NOZZLE POSITION HORIZONTAL STABILIZER POSITION	WING SWEEP ANGLE HORIZONTAL STABILIZER POSITION VECTORED THRUST NOZZLE POSITION SPEED BRAKE POSITION AILERON POSITION	WING SWEEP ANGLE HORIZONTAL STABILIZER POSITION VECTORED THRUST NOZZLE POSITION	WING SWEEP ANGLE HORIZONTAL STABILIZER POSITION AILERON POSITION RUDDER POSITION
FLIGHT PARAMETERS	GROSS WEIGHT FUEL WEIGHT/DISTRIBUTION EXTERNAL STORE INVENTORY GUN FIRING INVENTORY MISSION TYPE	GROSS WEIGHT FUEL WEIGHT/DISTRIBUTION EXTERNAL STORE INVENTORY GUN FIRING EVENT MISSION TYPE	GROSS WEIGHT FUEL WEIGHT EXTERNAL STORE INVENTORY MISSION TYPE	GROSS WEIGHT EXTERNAL STORE INVENTORY

The use of the Air-Data Computer would eliminate redundant instrumentation by allowing data such as airspeed, altitude, sink speed, etc., to be tapped as it is monitered by the standard aircraft instruments.

Many of the flight parameters must be manually input via an alphanumeric keyboard or some equivalent device because these parameters would be costly to monitor electronically.

Bomber/Transport IAT Systems

Since bomber/transport aircraft are usually analyzed parametrically, the requirements for sensors and transducers are somewhat different than those listed (above) for the fighter/attack/trainer aircraft. The major types of input parameters for this class of aircraft are:

(1) Mission Type
(2) Mission Segment Type
(3) Data Block Type
(4) Load Condition Type
(5) Special Activities or Events

Referring to Sections VI and VII, it is noted that the *raw* usage parameters required to identify the above listed parametric activity parameters are:

(1) Altitude
(2) Airspeed
(3) Normal Acceleration
(4) Rate of Climb
(5) Fuel Flow
(6) Engine Power Level, and
(7) Various Control Surface Position Sensors

2. Software Capabilities and Requirements

Definitions

In this report, the term software refers to both the computer languages that are used in writing a program and to the individual programs that reside in the various μP's in the IAT system. The onboard and ground based μP's used in the system require operating system programs and utility programs which control the basic functioning of the μP's during operations. These programs can be viewed as housekeeping programs. Since in most cases, the onboard μP system will control a data acquisition system (sensors, transducers, signal conditioning units, multiplexer and analog-to-digital converter), a data acquisition system control program will be needed.

To function as an IAT system, the onboard μP system also requires one or more IAT programs. For convenience these programs may be classified as one of two types: (1) a data acquisition processing program which manipulates and stores the acquired data, and (2) a data analysis program which performs one of several kinds of analysis of the data.

The operating system and utility programs are usually specific to the microprocessor being used and are supplied by the microprocessor's manufacturer or a software house. The data acquisition system control program is, in general, specific to each aircraft IAT system because of differences in the selection of the sensors and transducers used to monitor the usage of the aircraft. Therefore, this control program is usually written by the designer of the IAT system. The IAT programs have been in the past developed independently by each prime contractor for their own aircraft. Furthermore, since all of these IAT programs have been developed for ground based large computers, the languages commonly used have been FORTRAN and COBOL.

Some of the above programs (operating system, utility, data system control) will be or are written in a low order language; that is, an assembly language which is always highly specific to the microprocessor model. IAT programs have been written both in high order languages (FORTRAN) and in low

order languages. If a standard low order assembly language is desired, then the selection of a specific microprocessor device is necessary. Because of the differences between low order and high order languages, the use of high order languages in any program which is to be loaded into the onboard μP will invariably require much more memory (RAM) space.

To sum up, assembly language (coded) programs require less resident memory space, are executed at higher speeds, are highly specific to the selected μP hardware, and are not commonly known among structural engineers. High order languages (FORTRAN) are well known to structural engineers, but would require more μP system memory, would not execute as fast as the assembly language code, and would require additional interfacing computer programs depending on how the FORTRAN code is to be used on the μP.

IAT System Options

First Generation IAT Systems

For simplicity, it can be reasonably assumed that the first generation IAT hardware system will require the programmer to use an assembly language. This feature does not preclude using such a system as an off-the-shelf item, but it will lengthen the program development schedule for the IAT programs. A first generation system like the A-10A STEMS™ and its existing programming can be modified and used as an off-the-shelf system for other aircraft models.

Second Generation IAT Systems

The second generation system should not be limited by the size of its memory. Therefore, such a μP system will be a true off-the-shelf system in that the user would have the option to use one of several higher order languages without penalty. At this time, it is not known what design requirements must be specified for the second generation μP system in order to permit real time processing and analysis of data while operating under a high order language generated code.

SECTION IX

FEASIBILITY OF MICROPROCESSOR-BASED IAT SYSTEMS TO PERFROM THE L/ESS FUNCTION

A number of microprocessor-based L/ESS system concepts were reviewed to determine, qualitatively, the capability of such systems to partially or completely perform the L/ESS function. The concept of using the μP system as a load condition analyzer, rather than as a simple recorder, is discussed in detail.

1. Dedicated L/ESS Systems

Present day L/ESS hardware systems are merely data recorders. These systems monitor and sample a large number of usage parameters (12 to 40), convert the analog signals to digital signals, and then store the digitized parameter time series on magnetic tape. The magnetic tape cassettes (which typically hold about 10 to 30 flight hours of data) are periodically removed from the aircraft and processed on the ground. Virtually no data processing, in terms of engineering or statistical analysis, is done by the current types of onboard L/ESS systems.

The first and most obvious concept for a μP-based L/ESS system is to use it as an analog of current digital magnetic multi-channel recorder systems such as the MXU-553 unit. In this role, the μP system has a serious handicap. That is, current solid-state memory devices (CMOS) are not dense enough to economically permit the onboard storage of as much data as can normally be stored on magnetic tape. In terms of data density, magnetic tape is a superior medium. Large memories for the μP system can be designed using current solid state memory hardware but, because of the low memory density, unit costs will be high and the physical size of the unit may be excessive.

Assuming that 20 different parameters are to be sampled at an average rate of ten times a second and recorded for a period of 30 flight hours, the required amount of data memory is in the region of 22 million bytes if each parameter value is written into an addressable one byte word. This required memory size is a serious disadvantage for CMOS solid state memory devices. The obvious solutions are to reduce the number of data acquisitions and retrieve the data more frequently. The above memory size requirement is a rough estimate since various formatting schemes such as data compression have not been considered.

An alternate approach to this problem is to design a L/ESS unit with a moderate amount of memory (0.5 to 2.0 million bytes) and to accept the disadvantage of the more frequently required retrieval of data from the unit.

Current developments in Very Large Scale Integrated circuitry (VLSI) make it likely that within a few years memory devices having a density ten times current densities will be available. The use of these VLSI memory devices will make the μP L/ESS system practical, cost effective, and equivalent to current tape storage capability.

The problem of massive data storage requirements for the L/ESS system can also be attacked by using the μP system to analyze the L/ESS data as they are monitored; eliminating the need to store the raw data, and storing only the pertinent results. In Table 21, System 8 (Load/Environment Data Processor) is such a concept. Its basic function is to analyze the continuous L/ESS data and identify a sequence of predefined load conditions correlated to a number of key parameters such as normal load factor, altitude, mission segment type, etc., thus forming a discrete time series of the load conditions and parameters. To accomplish this, the μP system must be capable of storing and executing an extensive computer program designed to analyze the incoming raw data in a real-time or semi-real time mode. Obviously, various loads analysis programs can be used. The only restriction would be the computational power of the μP and the demands made on the μP memory by the loads analysis program.

TABLE 21. SYSTEM OUTPUT AND FUNCTIONS FOR THE O
SUBSYSTEMS FOR THREE TYPES OF MICROPR
SYSTEMS.

SYSTEM	TYPE OF ONBOARD AIRCRAFT MICROPROCESSOR SYSTEM	ONBOARD AIRCRAFT SYSTEM FUNCTION	TYPE O
6	BASIC L/ESS RECORDER	MONITOR AND RECORD AIRCRAFT'S RESPONSE, FLIGHT, AND CONFIGURATION PARAMETER TIME HISTORIES	COMPRESSED AND C
7	COMBINED L/ESS RECORDER AND DATA PROCESSOR	MONITOR AND RECORD AIRCRAFT'S RESPONSE, FLIGHT, AND CONFIGURATION PARAMETER TIME HISTORIES	COMPRESSED AND C
		PROCESS A NUMBER OF KEY PARAMETERS TO GENERATE: (1) PARAMETER EXCEEDANCE DATA (2) MULTI-PARAMETER CORRELATION DATA	CUMULATIVE AND I CORRELATED BY KE LO AL AI WE OT
8	LOAD/ENVIRONMENT DATA PROCESSOR	MONITOR AND TEMPORARILY STORE SELECTED RESPONSE, FLIGHT, CONFIGURATION, AND MISSION PARAMETER TIME HISTORIES	LOAD CONDITION OC CORRELATED BY KEY
		PROCESS THE ABOVE PARAMETER TIME HISTORIES TO GENERATE LOAD CONDITION TIME HISTORIES AND CORRELATE THESE HISTORIES WITH VARIOUS KEY PARAMETERS (1) BASED ON LARGE NUMBERS OF PREDEFINED LOAD CONDITIONS (2) DEFINED IN TERMS OF KEY USAGE PARAMETERS	LO AL AI GR EX AI TE OT AND BY ACTIVITY PA MIS MIS SP

LE 21. SYSTEM OUTPUT AND FUNCTIONS FOR THE ONBOARD AND GROUND BASED SUBSYSTEMS FOR THREE TYPES OF MICROPROCESSOR BASED L/ESS SYSTEMS.

ONBOARD AIRCRAFT SYSTEM		GROUND BASED SYSTEM
FUNCTION	TYPE OF SYSTEM OUTPUT	TYPE AND FUNCTION
R AND RECORD AIRCRAFT'S RESPONSE, , AND CONFIGURATION PARAMETER ISTORIES	COMPRESSED AND CORRELATED PARAMETER TIME HISTORIES	TYPE: (1) DATA RETRIEVAL SYSTEM (2) DATA PROCESSING FIELD SYSTEM (3) BULK DATA TRANSMISSION SYSTEM (4) FINAL BULK DATA PROCESSING SYSTEM FUNCTIONS: (1) RETRIEVAL AND TRANSMISSION OF DATA (2) ARITHMETICAL PROCESSING (3) FORMATTING OF DATA FOR REPORTS AND PERMANENT COMPUTER STORAGE
R AND RECORD AIRCRAFT'S RESPONSE, , AND CONFIGURATION PARAMETER ISTORIES	COMPRESSED AND CORRELATED PARAMETER TIME HISTORIES	
S A NUMBER OF KEY PARAMETERS TO GENERATE: PARAMETER EXCEEDANCE DATA MULTI-PARAMETER CORRELATION DATA	CUMULATIVE AND INCREMENTAL PARAMETER EXCEEDANCE DATA CORRELATED BY KEY PARAMETERS SUCH AS: LOAD FACTOR ALTITUDE AIRSPEED WEIGHT OTHERS	
R AND TEMPORARILY STORE SELECTED RESPONSE, T, CONFIGURATION, AND MISSION PARAMETER ISTORIES SS THE ABOVE PARAMETER TIME HISTORIES TO GENERATE CONDITION TIME HISTORIES AND CORRELATE THESE ORIES WITH VARIOUS KEY PARAMETERS BASED ON LARGE NUMBERS OF PREDEFINED LOAD CONDITIONS DEFINED IN TERMS OF KEY USAGE PARAMETERS	LOAD CONDITION OCCURRENCE DATA CORRELATED BY KEY PARAMETERS SUCH AS: LOAD FACTOR ALTITUDE AIRSPEED GROSS WEIGHT EXTERNAL STORES CONFIGURATION AIRCRAFT CONTROL SURFACES CONFIGURATION TIME OTHERS AND BY ACTIVITY PARAMETERS SUCH AS: MISSION TYPE MISSION SEGMENT TYPE SPECIAL EVENT	

As a simplified case, assume that in one hour of flying, 500 peak/valley and intermediate load conditions are identified and correlated to nine usage parameters which occur simultaneously. This results in 5000 data items. For 30 hours of flying (approximate monthly average for fighter aircraft), the number of data items stored will be 150,000. This number is much less than the number of data items that have to be stored if all raw data were retained. Memory space would have to be allocated for the analytical program and although the space requirement can not be accurately estimated it is within the limits of the state-of-the-art systems. This concept is discussed in detail in Subsection 3 below.

System 7 (Combined L/ESS Recorder and Data Processor) as outlined in Table 21 is a hybrid system and many of the comments made above apply.

2. Piggybacking a Small L/ESS System on an IAT Microprocessor System

If adequate data memory capacity is available, a small L/ESS program can be piggybacked onto the IAT μP system. This has in fact been accomplished by Northrop for the A-10A IAT system [34,35,36], which has the capability of recording three types of L/ESS data. These are: (1) Normal acceleration load factor (n_z) cumulative exceedance table, (2) Lateral acceleration load factor (n_y) cumulative exceedance table, and (3) Cumulative stress exceedance tables for four structural control points.

The normal load factor range is divided into eight load factor bands, while the lateral load factor range is divided into ten (five positive and five negative) load factor bands. The stress range is divided into twelve bands covering the range from the greatest expected compression stress to the greatest expected tensile stress. The data can be retrieved after each flight, and the ground based retrieval unit has the capability to normalize all three exceedance tables to 1,000 flight hours.

The above L/ESS data can be used only to verify the predicted composite mission mix spectra. Since the data are not categorized by mission type, it cannot be used to verify the crack growth effects of each type of mission.

The amount of data memory required for the above is very small though the program memory space requirement is significant. The program can be easily expanded to identify the various mission types and to assign a set of L/ESS data to each mission type.

3. A Concept for External Load Data Monitoring Microprocessor Systems

External air loads are generally identified by load condition; that is, a set of physical conditions or parameters which specify the aircraft's instantaneous geometric configuration, attitude and position in three-dimensional air space, linear and angular motions and accelerations, and inertial forces. By definition, all forces acting on the aircraft are in balance.

A single loading condition describes a single static load design case while a set of various loading conditions are required to describe the fatigue load design cases. This is analagous to using single snapshots versus using a series of cinematic picture frames. The real life situation is even more complicated because the aircraft experiences intermediate loading states as it transitions from one defined and recognizable loading condition to another defined and recognizable loading condition. Futhermore, each grossly defined loading condition is made up of a time-series of more finely defined loading conditions. For example, if an aircraft enters a symmetrical pull-up, (1) its configuration, inertial loads, and lateral motions and accelerations may not change at all, (2) its airspeed and altitude may change little, but (3) its angle of attack and normal acceleration factor will change considerably from the time the maneuver is started to the time it is completed. As the aircraft transitions from a normal load factor of one to a normal load factor of seven, aeroelastic effects on the swept wing may cause changes in the shape of the bending moment distribution and the location of the wing's center of pressure. Therefore, the symmetrical pull-up condition is actually a series of conditions with the normal load factor, airspeed, and angle of attack being the more important correlating parameters. If swept wing aeroelastic effects related to normal load factor are important, then the high g symmetrical pull-up condition

will be different than the intermediate or low g symmetrical pull-up condition. Since changes in the bending moment distribution (and probably in the torque distribution also) will affect the stresses on the wing structure, the moment distribution becomes an important consideration to the analyst who is attempting construct a design fatigue load history. In general terms, the problem is one of defining a design fatigue load history and a spectrum in the terms of occurrences of clearly defined loading conditions which are also related to specific mission profile segments and key operational usage parameters.

The concept proposed here is to use a μP based system to sense and record the occurrences of a family of predefined load conditions. Such a concept is shown in Figure 35. The μP system must be designed to sense, condition and digitize a number of instrumentation signals representing the aircraft' response and configuration parameters. Program logic will be used to examine e of the individual parameters both singly and in combination with other parame . and by a process of logical elimination or differential diagnoses determin e identity of the predefined loading condition which matches the recorde ition to within certain limits. For example, a symmetrical maneuver can be logically detected if the following parameters change from their steady state or previous state values.

Normal load factor	n_z
Air Speed	V
Altitude	H
Angle of Attack	α
Pitching Velocity	q
Pitching Acceleration	$\dot{q}$
Elevator/Stabilator Deflection	δ_e

In addition, the following parameters do not change from their steady or previous state values for a symmetrical maneuver.

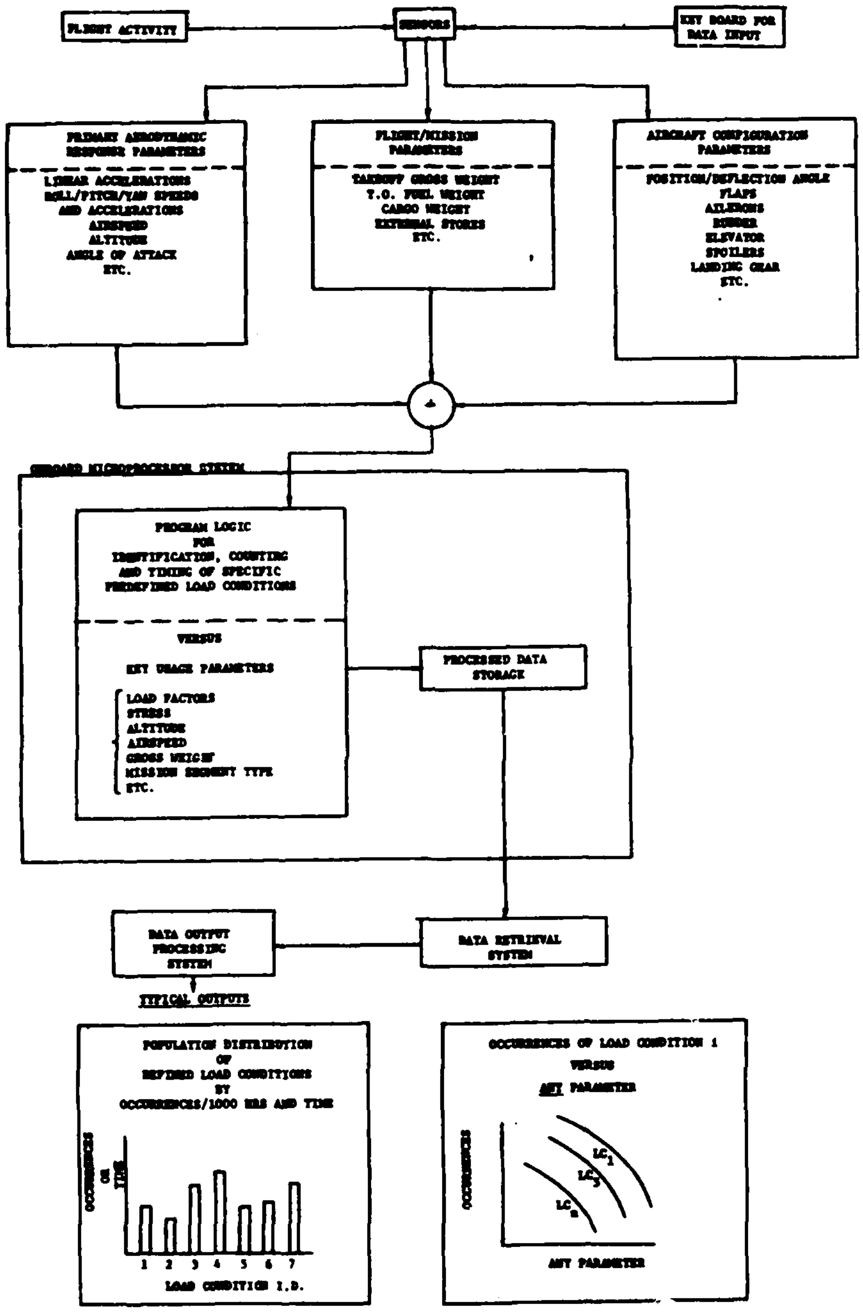

Figure 35. Advanced Microprocessor L/ESS System Concept for Load Condition Type Data

Lateral Load Factor	n_y
Weight (Calculated)	W
Yaw Angle	β
Rolling Velocity	p
Rolling Acceleration	$\dot{p}$
Yawing Velocity	r
Yawing Acceleration	$\dot{r}$
Rudder Deflection	δ_r

Some of the above parameters are obviously redundant. For example, both rolling velocity and acceleration are not needed.

It is usually necessary to correlate the identified load condition with a key parameter such as normal load factor, calculated gross weight, altitude, etc. The minimum data required to be stored in the IAT or L/ESS μP system memory are the identification code for the load condition, and the value of the correlated parameters. If, as expected, the chief correlated parameter is the normal load factor and it is desired to have 13 load factor memory bins representing a range of n_z from -3 to 10 in increments of 1g, then for each expected predefined loading condition, 13 memory locations must be allocated to hold the number of occurrences in each n_z interval. If a total of 100 loading conditions of all types are to be correlated with n_z then 1300 memory locations are required.

The logic required to identify other types of maneuver loading conditions is in principle no more difficult than the above example. In Figure 35 several forms of summed load condition occurrence output data for a certain recorded time period are shown. These may include a population distribution of all predefined load conditions that occurred and cumulative occurrence tables or curves of each load condition versus a correlated parameter.

Data needed for the development of the diagnostic logic must come from the structural engineering flight test program required by MIL-STD-1530A; that is, the flight and ground loads survey and the dynamic response tests.

These aircraft flight and ground tests should provide all of the parameter data needed to define (1) loading conditions and related load distributions, (2) parameter steady state threshold values, (3) parameter measurement tolerances, and (4) the required minimum and economical parameter set size.

The detection of gust load conditions is somewhat different. Conventionally, gust conditions are defined in terms of differential gust parameters (vertical air velocity or incremental normal load factor) superimposed on a steady state maneuver load condition. The problem is to develop program logic which can distinguish between maneuver and gust loading. For example, gust loading usually occurs with higher frequencies than maneuver loading and this characteristic may be used to detect gust loading. But in some cases of low altitude terrain-following flying, the amplitude and frequency of gust loading may be of the same order of magnitude as the terrain-following maneuver loading. Further, small relatively rigid aircraft will respond quite differently to gusts than will a large flexible aircraft. In summary, program logic to detect gust load conditions can be developed, but data from the dynamic response engineering flight tests are necessary and additional L/ESS instrumentation may be required for some types of aircraft.

SECTION X

CONCLUSIONS

1. Advanced Microprocessor-Based IAT Systems

A number of microprocessor (μP) based IAT conceptual systems and an existing μP-based system currently going into in-service testing were developed and/or studied to examine their effectiveness and capability to accomplish the IAT goals and to correct the problems associated with current in-service systems. Based on this study it has been concluded that several different types of microprocesser based systems can satisfactorily accomplish the goals of IAT and surpass the overall performance of existing conventionally equipped systems.

The advantages of the μP-based onboard IAT system are that it can

(1) Eliminate or reduce the logistical, manpower, and reliability problems which now affect existing IAT programs

(2) Be retrofitted into existing aircraft IAT programs with little or no change in the older system's logic and crack growth analytic methodology

(3) Improve the accuracy and reliability of IAT input parameter acquisition and of the IAT cumulative crack growth analysis

(4) Expand the versatility and power of IAT crack growth analysis by permitting real time cycle-by-cycle crack growth analysis onboard the aircraft for a large number of structural control points, and by permitting a greater variety of output parameters to be calculated, thus improving the Force Management system

(5) Perform different IAT and L/ESS functions using the same μP system because of its capacity to execute different IAT software programs

(6) Change its IAT function (or program) as needed to satisfy new or revised IAT methods or FM goals because of the μP's ability to be reprogrammed

The most significant disadvantage of the μP based system is the cost of system design development and system hardware procurement costs. For some aircraft systems, the data acquisition subsystem would be the same for both the μP system and the conventional older systems so that the additional system development and procurement costs would be limited to the onboard μP data processing subsystem and the ground based support subsystem. In other cases, the data acquisition subsystem would be introduced into an aircraft where none previously existed. Although it is strongly believed that the μP-based IAT system will effect significant field level and depot level operational labor cost savings, the lack of readily available, reliable cost figures for these items makes it impossible to evaluate the IAT operational manhour savings in comparison to the increased development and procurement costs.

The single most important cost savings which could be attributed to the μP IAT system would be due to the extension of the service life of the force because of the improved effectiveness of the force structural management program. This cost savings will greatly overshadow any possible cost savings due to improved IAT operational efficiencies.

2. Microprocessor-Based Load/Environment Spectra Survey Systems

In this study the concept of using the μP system for the L/ESS function was examined. It is concluded that although the μP can definitely be used as the central processing unit for a multi-channel recorder system, its capability is limited by the expense of providing adequate solid-state memory. The onboard, long term data storage requirement is very large - on the order of 20 to 100 million bytes. For example, the design of a μP-based L/ESS system as analog of the MXU-553 multi-channel recorder is technically feasible but its economic viability is in doubt because of the types of solid state memory devices that are available, their memory densities, and costs. At this time, digital magetic tape is still the superior means of storing data. This suggests the alternate concept of using a nonremovable magnetic tape unit as the long term memory for the L/ESS μP system with only a limited amount of solid state short-term memory. Such a system would be able to provide sufficient data storage to permit twenty to forty hours of flying between data retrievals.

One of the significant conclusions of this study is that the µP-based L/ESS device could be used as a radicially different type L/ESS device by programming the µP to function as a real-time load condition analyzer. In this concept, the µP would analyze, both arithmetically and logically, all the input parameter time histories while the data reside in temporary memory and, using its resident program, identify and construct a time history of the various load conditions experienced by the aircraft. The original raw input parameter data would not be stored in memory, thus greatly reducing the system's memory needs. In effect, this µP system would be performing many of the loads analysis functions now performed on large computers.

3. Versatility of the Microprocessor-Based IAT System

This study has shown that the acknowledged logical and computational power of the µP will enable it to be used in a varity of different tracking roles. It can function as an IAT input parameter acquisition system like the statistical accelerometer system used in the F-4 IAT program. It can function both as an input parameter acquisition system and as an analytical processor - a total onboard system as on the A-10A STEMS™ program. It can also function as an alternate type of IAT input parameter acquisition system - as a logic processor to determine the IAT mission activity parameters, as for example, on the large aircraft IAT programs.

This versatility is attributable to the capability of programming the µP-based IAT system to perform a large variety of IAT functions.

SECTION XI

RECOMMENDATIONS

1. IAT Systems

(1) All future IAT systems should be designed to use microprocessor devices as the system's central data processing unit because of the microprocessor's effectiveness in processing and analyzing data and its capability to improve the efficiency of the logistic aspects of the IAT program.

(2) Two functional types of microprocessor-based IAT systems should be developed for general use: one system serving only as an input parameter data acquisition unit and the other system serving both as a data acquisition unit and as a cumulative crack growth analyzer.

(3) All IAT microprocessor systems should be designed to process and store a limited amount of L/ESS data to supplement the IAT output parameter data.

(4) A generic IAT hardware system could be designed as a group of separate functional hardware modules capable of being separately linked together to the microprocessor central unit to facilitate the optional assembly of a number of different subsystems into a single system capable of performing one or several functions. The functional units would be:

(a) The basic IAT input parameter data acquisition and cumulative crack growth analyzer unit

(b) An add-on memory unit to expand the capacity of the basic IAT system

(c) An engine maintenance monitoring unit, and

(d) A crash survivable short term memory unit

(5) The feasibility of effectively transmitting bulk IAT and L/ESS data from the field to the Air Logistic Center(s) should be investigated by designing, constructing, and service testing a prototype bulk data transmission system.

(6) The feasibility of a decentralized IAT data management system wherein the prime Air Logistic Center force management organizations would receive processed and analyzed IAT data directly from the field IAT systems should be studied in detail by designing, constructing, and service testing a prototype system.

2. L/ESS Systems

(1) All future L/ESS systems should be designed to use microprocessor devices as the system's central data processing unit.

(2) A microprocessor-based L/ESS system having a cost effective and reliable long term data memory system capable of storing at least thirty flight hours of at least twenty five different parameter time histories should be designed, prototyped, and service tested.

(3) An onboard load condition analyzer type of L/ESS system should be studied in order to realistically determine the feasibility and utility of such a L/ESS system concept.

(4) Standard data compression techniques should be developed, defined, and specified for future raw data recording types of L/ESS systems.

APPENDIX A

C-5A TRANSPORT IAT AND FM DATA SYSTEM

This appendix describes in detail the C-5A IAT/FM data base as developed by the University of Dayton [25,26]. Because of its extensive nature and variety of data outputs, this IAT/FM data base description can serve as a model for a large FM data program. It is not recommended that this model be followed blindly. However, it demonstrates the variety of IAT/FM data representations which can be used.

1. Summary Data and Statistics

The following section describes the summary report which presents summaries for quick review of major data items. The purpose of the report is to identify broad trends which will or may effect operational planning, force safety, or logistic plans. Most of the data are presented graphically for ease of review.

The summary report includes the following data items.

1) Average cumulative flight hours per aircraft versus mission types (bar graph).

2) Average cumulative number of flights versus mission type (bar graph).

3) Ratio of reported-to-planned average flight hours per aircraft for six quarters (point graph).

4) Ratio of reported-to-planned average number of flights per aircraft for six quarters (point graph).

5) Ratio of reported-to-planned average number of landings per aircraft for six quarters (point graph).

6) Ratio of reported-to-planned average pressure cycles per aircraft for six quarters (point graph).

7) Ratio of reported-to-planned average hours in refueling environment per aircraft for six quarters (point graph).

8) Ratio of reported-to-planned average refueling events per aircraft (point graph).

9) Ratio of reported-to-planned average flight hours per aircraft versus mission type (point graph).

10) Ratio of reported-to-planned average flights per aircraft versus mission type (point graph).

11) Cumulative flight hours by year for high time, average, and low time aircraft (line graph).

12) Cumulative flight hour distribution for the force (bar graph).

13) Cumulative landings by year for the high time, average, and low time aircraft (line graph).

14) Cumulative landing distribution for the force (bar graph).

15) Total landings versus flight hours for aircraft having the greatest, average, and least number of landings (line graph).

16) Utilization rate (flight hours per year) distribution (bar graph).

17) Number of flight hours per landing versus cumulative flight hours for the highest, average and lowest time aircraft (line graph).

18) Flight hours per landing versus quarterly or yearly flight hours for the highest, average, and lowest time aircraft (line graph).

19) Aircraft ranking with respect to time-to-maintenance-action versus calendar time for a specific maintenance action item for several planned mission mix usages (line graph).

20) Man-hours per quarter required for specific maintenance action item versus calender time for several planned mission mix usages (bar graph).

21) The rate of change of schedule for a specific maintenance action as a result of individual aircraft usage (line graph).

2. <u>Past Usage Characterization Statistics by Mission/Flight Parameters</u>

Past usage parameter statistics use the IAT mission type and primary (flight) parameters to compare actual use to planned mission parameter usage and shows trends indicating the rate of change in the mission parameters. Where required the usage statistics are related to the command, base, and wing or any combination of associations. These data items are in tabular form except as noted.

1) Trend analysis of major mission/flight parameters by quarters, yearly sum by quarters, and yearly sum. The parameters are:

Number of aircraft
Flight hours
Airframe hours
Flight duration
Number of flights
Number of landings
Gross weight, T.O.
Cargo weight, T.O.
Fuel weight, T.O.
Fuel weight, Landing
Altitude, average maximum
Take-off Center of Gravity, average
Landings, full stop
Landings, TAG
Landings, substandard
Number of fuselage pressure cycles
Number of aerial refueling events
Number of wet aerial refueling events
Hours: dry aerial refueling
Hours: wet aerial refueling
Transferred weight, aerial refueling
Average for all aerial refueling events

For each of the above, the parameters are usually reported as averages for the aircraft, averages for the flight, and as the ratios of reported-to-planned per aircraft or flight.

2) Cumulative flight hours versus calendar time for highest, average, and lowest time aircraft with projections (line graph (l.g)).

3) Population distributions for flight hours, cargo weight, number of flights, and number of landings (bar graph (b.g.)).

4) Trend of average planned and reported flight hours for six quarters (b.g.).

5) Trend of average planned and reported flights for six quarters (b.g.).

6) Trend of average planned and reported landings for six quarters (b.g.).

7) Trend of average planned and reported pressure cycles for six quarters (b.g.).

8) Trend of average planned and reported aerial refueling hours for six quarters (b.g.).

9) Trend average planned and reported aerial refueling events for six quarters (b.g.).

10) Ratio of reported/planned average flight hours per aircraft for six quarters (point graph (p.g.)).

11) Ratio of reported/planned average flights per aircraft for six quarters (p.g.).

12) Ratio of reported/planned average landings per aircraft for six quarters (p.g.).

13) Ratio of reported/planned average pressure cycles per aircraft for six quarters (p.g.).

14) Ratio of reported/planned average hours in refueling environment per aircraft for six quarters (p.g.).

15) Ratio of reported/planned refueling events per aircraft (p.g.).

16) Analysis of flight, airframe and flight hour averages per aircraft, and flight duration per flight by mission type.

17) Analysis of landing averages per aircraft by mission type.

18) Analysis of cargo, fuel, and gross weight, and productivity averages per aircraft by mission type.

19) Analysis of altitude, pressure cycle and airspeed averages per aircraft by mission type.

20) Analysis of aerial refueling averages and contour flight hours per activity by mission type.

21) Analysis of landing averages per flight by mission type.

22) Analysis of cargo, fuel, and gross weight, productivity, and C. G. (%MAC) averages per flight by mission type.

23) Analysis of altitude, pressure cycle, airspeed and take-off, C.G. averages per flight.

24) Analysis of aerial refueling averages per flight by mission type.

25) Cumulative average flight hours per aircraft versus mission type (b.g.).

26) Cumulative average flight hours per aircraft versus mission type (b.g.).

27) Percentage of flight hours versus mission type (b.g.).

28) Percentage of flights versus mission type (b.g.).

29) Ratio of reported/planned average flight hours per aircraft versus mission type (p.g.)

30) Ratio of reported/planned average flights per aircraft versus mission type (p.g.).

31) Individual aircraft cumulative usage ranked by serial number (refer to Item 1 above for a list of all the included parameters).

32) Cumulative flight hours versus calendar time for highest, average, and lowest time aircraft (l.g.).

33) Cumulative flight hour distribution (b.g.).

34) Cumulative landings per aircraft versus calendar year for the highest, average, and lowest time aircraft (l.g.).

35) Cumulative landings distribution (b.g.).

36) Total landings versus flight hours for highest, average, lowest time aircraft (l.g.).

37) Utilization rate (in flight hours per year) distribution (b.g.).

38) Flight hours per landing versus cumulative flight hours for the highest, average, and lowest time aircraft (p.g.).

39) Flight hours per landing versus quarterly flight hours for the highest, average, and lowest time aircraft (p.g.).

40) Individual aircraft data for one flight.

3. Past Usage Characterization Statistics by Mission Type

Past mission type usage statistics are used to show deviations in the usage mission types compared to the planned mission types which are the basis for the crack growth analysis. The accuracy of the IAT analysis and its impact on FM depend on the amount of deviation. The data items are in tabular form except as noted in which case they are in the form of bar graphs (b.g.).

1) Reported flight time, number of flights and flight duration with the ratio of reported/planned usage by mission type.

2) Cumulative distribution of flights by percent and hours versus mission type (b.g.).

3) Quarterly distribution of flights by percent and hours versus mission type.

4) Reported landings - full stop, touch and go, substandard and total with the ratio of reported/planned usage by mission type.

5) Number of missions versus mission type (b.g.).

6) Cumulative usage-number of landings versus mission type (b.g.).

7) Cumulative missions versus mission type (b.g.)

8) Quarterly usage: number of landings versus mission type (b.g.).

9) Reported gross weights and cargo weights for take-offs and landings with their ratios of reported/planned usage by mission type.

10) Reported fuel weight for take-offs and landings, center of gravity location, and productivity with the ratio of reported/planned usage by mission type.

11) Cumulative planned and actual weight loads (cargo, T.O. fuel, and final landing fuel) by mission type (b.g.).

12) Quarterly planned and actual weights (cargo, T.O. fuel, and final landing fuel) by mission type (b.g.).

13) Distribution of take-off cargo weight by mission type.

14) Distribution of take-off weight by mission type.

15) Distribution of landing gross weight.

16) Distribution of landing cargo weight by mission type.

17) Distribution of landing fuel weight by mission type.

18) Distribution of aerial refueling transferred weight by mission type.

19) Distribution of cruise altitude by mission type.

20) Distribution of cruise airspeed by mission type.

21) Distribution of take-off C. G. (% MAC) by mission type.

22) Distribution of pressure cycles by mission type.

23) Distribution of take-off gross weight by mission type.

24) Reported airspeed, altitude, pressure cycles and contour flight hours with their ratios of reported/planned usage by mission type.

25) Individual aircraft usage data summary by mission type.

26) Mission data summary.

27) Distribution of parameters by mission type.

4. Individual/Force Damage Tolerance Status

The individual/force damage tolerance data and statistics describe the rate at which individual aircraft and the force accumulate crack growth damage. The data reported are critical and current crack lengths, planned and actual (yearly) damage rates and relative (actual/planned) damage rate ratios for each aircraft, each structural control point analyzed, and selected control points for the force.

Based on the above cumulative crack growth and the damage (crack growth) rates, the remaining service life and the remaining time to maintenance actions are calculated. The remaining life is based on a projected mission type mix which was analyzed to give the projected crack growth rate (per hour or per year). The fractional life expended to-date is defined as the total (initial) life to failure minus the current (to-date) life to failure all divided by the total (initial) life to failure. Most of the data items are presented in tabular form.

1) Relative damage rate at each location on aircraft S/N for the time period of one year.

2) Relative damage rate at selected control point analysis locations for all aircraft for the time period of one year.

3) Average normalized crack growth rate as a function of time (l.g.).

4) Individual aircraft life remaining ranked by years remaining.

5) Definition of the remaining service life and its rate of change based on the last five years of service for all aircraft at a critical analysis control point.

6) Definition of the relative rate at which remaining service life capacity is being depleted at each critical location for aircraft S/N based on a time period of one year.

7) Definition of the relative rate at which remaining service life capacity is being depleted at a critical analysis control point location for all aircraft based on a time period of one year.

8) Quarterly distribution of aircraft structural life remaining as of (Mo/Yr) (b.g).

9) Individual aircraft fracture status for a specific analysis control point.

10) Individual aircraft expended life fraction projection number for various control point analysis locations.

11) Individual aircraft projection expended life fraction for a control point location.

5. Maintenance Actions and Schedules

The maintenance action and schedule data items focus on the near term scheduling requirements. The data define the when, where, and how of the structural maintenance and inspection requirements as well as the manpower requirements necessary for completing the action on schedule. The reports have been set up to accommodate the production engineering requirements which result from the individual aircraft tracking system. Force wide requirements for a given maintenance action are provided so that if an aircraft must remain on-station for some additional time, continuity in the schedule can be maintained.

1) Depot schedule.

2) Action schedule for programmed depot maintenance (PDM) ranked by planned starting date.

3) PDM plan for fiscal year.

4) Action item index for aircraft by serial number.

5) Force inspection status by inspection area.

6) Fiscal year 19XX inspection plan.

7) Individual aircraft inspection schedule for analysis locations ranked by inspection date.

8) The influence of modification rate on the number of aircraft that will be modified in a given period of time (l.g.).

9) Total number of hours accumulated in unmodified aircraft beyond their planned modification hours as a function of time (l.g.).

The data items listed below present data that describe the requirements for structural maintenance/inspection over a longer time than is necessary to establish current budgets. The formats have been designed with an apprecia- tion for potential usage operational changes and to directly indicate to the force manager the impact of current and past usage on the longer term mainten- ance shedule. Reference is made to time-to-action relative to the remaining structural life until retirement because it is felt that financial benefits might be substantial if the force manager retires some aircraft earlier than planned and utilizes some other aircraft at a higher untilization rate during phase-out.

1) Defining the dates and relative rates at which scheduled maintenance (Item 6) changes as a result of individual aircraft usage for all aircraft.

2) Relationship between planned retirement schedule and the modification schedule for safety-of-flight critical structure.

3) Schedule for various maintenance actions for a defined usage actions required prior to retirement (p.g.).

4) Influence of type of usage on the maintenance schedule for a specific action (p.g.).

5) Years of life remaining prior to taking various actions (p.g.).

6) Fractional life remaining with respect to initial (roll out) life for retirement conditions (p.g.).

7) Additional service years gained by incorporating modifications, assuming that structure is retired as planned (p.g.).

8) Ratio of years to critical action for critical items to years until retirement.

9) Relationship of the years until individual maintenance action to the remaining life in the aircraft (p.g.).

10) Relationship between planned retirement schedule and inspection schedule for safety of flight critical structure.

11) Schedule for inspection actions for a defined usage (p.g.).

12) 15-year inspection plan.

Two data items are used to define the inspection and modification status. The focus of these data items is to define overdue conditions relative to a predetermined allowable. The two items cover, respectively, overdue condition at the time the analysis was conducted and the overdue condition at the time of the next planned inspection period. Such data items should give the force manager immediate information relative to modifying the time of the next planned inspection or the rate at which the aircraft is being used.

1) Current inspection status as of a future date.

2) Inspection at next planned inspection period.

The utility data items (below) are designed to give the force manager access to aircraft location by base station, indication of the quantity of aircraft data collected (and validated), as well as component tracking information when appropriate.

1) Individual aircraft locator.

2) Reporting rate summary - individual aircraft.

3) Reporting rate summary - mission by individual aircraft.

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